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Final Report

Assessment of a Constructed Bulrush Wetland for Treatment of Cattle Waste: 1991-1994

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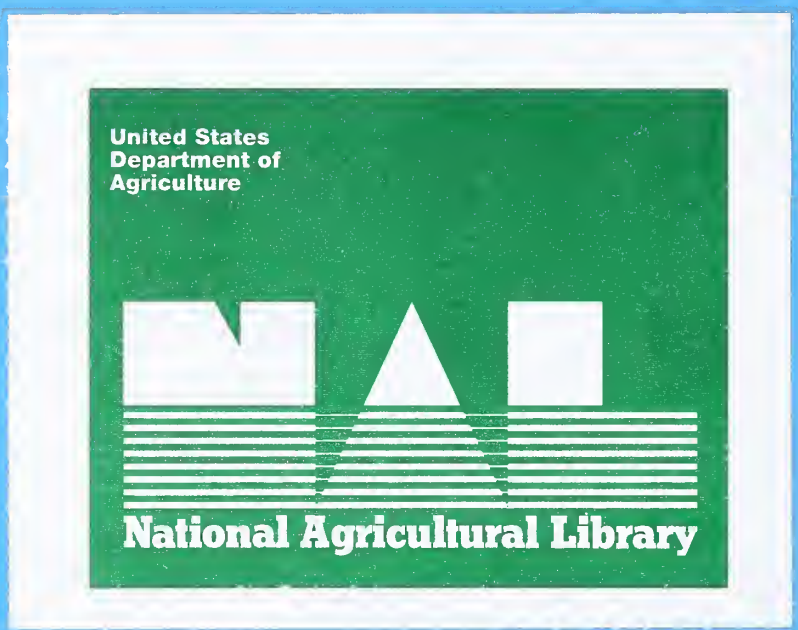

ASSESSMENT OF A CONSTRUCTED BULRUSH WETLAND FOR TREATMENT OF CATTLE WASTE: 1991-1994[1]

Final Report

Accomplished as part of the Demonstration Erosion Control (DEC) in the Yazoo Basin

by

Water Quality and Ecological Processes Research Unit
National Sedimentation Laboratory
Agricultural Research Service
U. S. Department of Agriculture
in
cooperation with the
Mississippi Natural Resources Conservation Service

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EXECUTIVE SUMMARY

In recent years, the ability of natural and constructed wetland ecosystems to improve water quality from a wide variety of degraded sources has become evident. With increasing public concern and resulting legislative controls regulating water pollution, the use of constructed wetlands as a cost-effective, low maintenance technology to treat contaminated waters has become popular. The role of aquatic plants in water quality improvement has been thoroughly documented with respect to removing nutrients, organic chemicals, heavy metals, biological and chemical oxygen demand, bacteria, and waste solids. Design criteria for constructed wetlands are still undergoing extensive study, and optimal configurations for specific regions of the United States and types of pollution are being researched. A constructed wetland for treatment of dairy wastewater was built by the USDA Natural Resources Conservation Service (formally Soil Conservation Service) and the Agricultural Research Service in DeSoto County, MS during 1990. Three parallel wetland cells, planted with giant bulrush (*Scirpus validus*), were monitored for 36 months while receiving wastewater inputs from a <100-head dairy operation. Measures of physical and chemical water quality, BOD, COD, and coliform bacteria were recorded, and average seasonal pollutant and nutrient-trapping efficiencies for the constructed wetland cells were calculated. Averages from inflow and outflow measurements for the entire study period yielded the following overall results. Discharge from the system occurred at 103 out of 181 observations (57% of observations). Suspended solids were reduced 60%, while dissolved solids were reduced only 22%. Filterable ortho-phosphorus was reduced 42% and total phosphorus was reduced 53%. Ammonia nitrogen declined 82%. Nitrate nitrogen concentrations increased by 14% because of ammonia reduction, though outflow concentrations were typically very low (mean = 0.10 mg/L). Carbonaceous biochemical oxygen demand ($CBOD_5$) and chemical oxygen demand (COD) were reduced 75 and 63 percent, respectively. Total chlorophyll was 78% less at discharge stations, and total coliforms decreased by 89%. Doubling the length of cell treatment by adding an identical companion cell in series for assessment during 1992 and 1993 showed the following differences in water quality as compared to original cell reductions: an added 23% drop in conductivity; a 20% increase in dissolved oxygen; a 20% added reduction in total solids, and 27% additional decrease in dissolved solids; 37% more reduction of filterable ortho-phosphorus concentrations, and 23% additional reduction of total phosphorus concentrations. There was also a 13% greater reduction of ammonia-nitrogen concentrations; nitrate-nitrogen concentrations decreased 52% as opposed to a 14% increase in original cells; BOD and total chlorophyll concentrations decreased by over 9%. Total coliforms were only slightly changed. Constructed wetlands have considerable potential as cost-effective on-farm waste management systems.

Keywords: wetlands, water quality, nutrient removal, coliforms, bulrushes

1. INTRODUCTION

Recent studies sponsored by the U.S. EPA documented over 150 constructed wetland systems currently in use within the United States for the treatment of municipal and industrial wastewater (Reed, 1991; Reed and Brown, 1992). Constructed wetland systems have also been installed to serve individual households and, at a larger scale, agricultural sources of wastewater. While these systems have become more prevalent owing to their relatively low cost, low maintenance requirements, and possible ecological benefits, it is likely that it will be several years before optimal design criteria are established.

The capabilities of aquatic plants and constructed wetlands to remove excess nutrients and other pollutants from waters have been well documented both in laboratory and field studies (Seidel, 1976; Wolverton and McDonald, 1981; Peverly, 1985; Oron, 1990; Kumar and Garde, 1990; Rogers et al., 1991; Tripathi et al., 1991; Zachritz and Fuller, 1993). However, a wide range of designs have been used, and climate specific studies (Reuter et al., 1992) and refined guidelines for implementing wetland systems targeted for specific situations are only lately emerging (Krider and Boyd, 1992; Holmes et al., 1992; Chen et al., 1992; Ulmer et al., 1992). Hamilton et al. (1993) present a recent general overview of constructed wetlands use.

Several studies have been conducted which can be used to compare efficiency of different species of aquatic vegetation for processing sewage or similar waste (Boyd, 1970; Boyt, et al. 1976; Lan, et al., 1992; Sheffield, 1967; Wolverton and McDonald 1975, Spangler et al. 1976). Gersberg, et al. (1986) found that bulrushes (*Scirpus validus*) and reeds (*Phragmites communis*) (in that order) were superior to cattails (*Typha*) in processing ammonia and BOD.

Processing and disposing of concentrated on-farm animal waste, a major source of water quality deterioration, is a concern of the Natural Resources Conservation Service (NRCS) and regulatory agencies. Several projects for evaluating the ability of constructed wetlands to process animal waste have been initiated across the United States. As a result, optimal design criteria for such future animal waste management systems may be forthcoming. The Mississippi NRCS and the Agricultural Research Service (ARS) National Sedimentation Laboratory in Oxford, Mississippi cooperated on an on-farm dairy waste treatment project which used a constructed bulrush wetland for processing. Herein we present findings from three years of operation and make suggestions for future design criteria for such systems.

2. DESCRIPTION OF STUDY SITE DEVELOPMENT AND ANNUAL TRENDS

The Alan Scott dairy farm is located in DeSoto County, in extreme northern Mississippi. During the study period a maximum of 100 cattle were milked twice daily in a concentrated animal feeding operation. Total runoff area for the milking parlor and concrete loafing area where animals were confined during milking was 351.5 m^2. Total waste production in this area was estimated at 10336 liters per day. Wastes drained through 15.24 cm (6 inch) diameter PVC pipe to a 42 m x 52 m settling lagoon. The lagoon received input from milking equipment and tank cleanings, milking barn washings, loafing area runoff, and rainfall (Table 1). Export from the lagoon, drawn from approximately 0.3 m below the water surface, traveled through 7.62 cm (3 inch) diameter PVC pipe to three parallel constructed wetland cells, each 6 m wide

and 24 m long (Figure 1). Wastewater entered the cells through a horizontal, perforated section of pipe which spanned the width of the cell to prevent short-circuiting or channel flow. The pipe was elevated 20 cm above the water surface to prevent settling of solids and to allow for easier periodic cleaning.

Land slope was such that only part of the bottom of the cells were excavated; the remainder of the bottom and levees was built from soil excavated from the lagoon. Construction occurred in April, 1990, and constructed wetland cells were planted immediately in bulrush (*Scirpus validus*) at 0.3 m intervals with rhizome cuttings purchased from a wildlife supply company. Subsequent rains, supplemented with water pumped from the lagoon and well water, maintained standing water in the cells for the remainder of the year. Water level in the lagoon increased slowly because of high evaporation rates and lateral seepage through levees until the basin sealed. An insufficient amount of water accumulated in the lagoon to allow a gravity fed water supply to the cells during 1990.

Bulrush growth in the cells was rapid. By September, 1990, the cells were covered by a uniformly dense monoculture with the majority of culms supporting flowering/seeding heads. Natural senescence occurred in November and December. Re-emergence of bulrushes from rhizomes occurred in February, 1991, through the litter created by the previous year's growth. Duckweed (*Spirodela polyrhiza*) spread to cover nearly all available water surface by May, 1991. In April, gravity flow from the lagoon to the wetland cells began functioning. Discharges to cells were calibrated to yield 3.0 L/min using in-line valves. Water depth in the cells was a maximum of 0.3 m.

Rapid water level decline in the anaerobic lagoon during summer, 1991, prompted a reduction of cell inflow rates to 0.5 L/min, but settling of solids in pipes and valves generally resulted in lower rates. Standpipes were fitted with threaded end caps containing orifices sized to achieve desired flow rates. Original valves were opened fully to prevent occlusion. Because of variations in flow a 4000 L constant head tank was placed on the lagoon levee and connected to the supply pipe to the cells. A timer-controlled electric pump maintained water in the tank, creating constant hydraulic head and, thus, producing constant inflow. Using this method, a cell inflow rate of 1.0 L/min. was implemented, and the frequency of remedial action was greatly decreased. Also during the summer, 1991, another cell, Cell 4, was constructed in series with Cell 1 to allow greater loading capacity and assessment of further treatment (Fig. 1).

In 1992 bulrushes emerged in late March, over four weeks later than during the previous year. Initial growth occurred only around the edges of wetland cells. Growth was sparse, especially where dead plant material from previous growth had become matted and submerged. Areas where previous plant materials were not compacted exhibited quicker, more even growth. Cells 2 and 3 developed fairly dense monocultures, but bulrushes in Cell 1 remained limited to shoreline areas through June. During July, dead plant material in the water column of Cell 1 was removed by rake, and water depth in the cell was lowered to approximately 10 cm in an attempt to stimulate plant growth to levels similar to the other two research cells. Growth occurred in the center of the cell, but these actions invalidated comparisons between Cell 1 (and as a result, Cell 4) for the Fall 1992 season; impacted data are not included in the calculated results.

Plants matured with seed between June and September, 1992 in all cells. Bulrushes in Cells 2 and 3 exhibited broadening areas of dead plants during August, September and October. This coincided with presence of a spotty fungus on many plant culms, and large numbers of grasshoppers in the culture. Cell 1, where bulrushes uniformly spread following dead plant material removal, remained mostly green and vigorous through the end of October. All bulrushes in the parallel cells succumbed to freezing temperatures by early December.

Plant growth in 1993 was first observed in mid-March, again initially limited to marginal areas in the cell. By May, cell growth was fairly uniform and dense in Cell 1 but was patchy in Cells 2 and 3. There were dense mats of decaying vegetation in Cells 2 and 3, so much so that in Cell 3 a large number of invasive plant species became established on the mats. Remedial actions to exterminate undesired plants and re-establish bulrush in Cell 3 excluded it from data comparisons from July 1993 through the end of the project. Moderate damage by grasshoppers and fungus attacks on bulrushes were noted after July. Bulrushes died following repeated frosts by the end of November 1993.

During the spring of 1994, bulrushes emerged during mid-March around each cell periphery. Bulrush growth for the year was sparse, appearing as isolated clumps scattered through the cells, with an encircling ring of rushes at the cell margins. The densest stand of rushes occurred in Cell 1 which had been raked of dead plant material two years earlier.

3. METHODS

Eighteen parameters were monitored at biweekly intervals from May, 1991 through April, 1994 (Table 2). Total rainfall for the two week period prior to sampling and lagoon water column depth were recorded. Lagoon samples were taken from the outflow control platform at a depth of 0.3 m below water surface. Flow rate, temperature, conductivity, dissolved oxygen, pH, sediment redox potential, total solids, dissolved solids, suspended solids, filterable ortho-phosphorus, total phosphorus, ammonia nitrogen, nitrate nitrogen, total chlorophyll, 5-day carbonaceous biochemical oxygen demand, and total coliforms were measured at cell inflow and outflow. In addition, early in the project 3 walkways were constructed equal distances apart in Cell 2 (Fig.1) so that in-cell measurements could be taken at intervals without disturbing the cell. Chemical oxygen demand was determined at all sampling sites quarterly. Water quality parameters were measured according to APHA (1989) guidelines (for further details, see Cooper et al., 1993). Cells did not continually discharge (due to evapo-transpiration, ground infiltration and seepage [Table 3]). When such times coincided with sampling visits, water quality samples and measurements from non-discharging outflow stations were taken by tilting the standpipe until flow occurred (discussed further below). For computing loading rates of pollutants, hydraulic load on individual cells was 1 cm/day (1440 L over 144 m^2 per day).

For purposes of computing seasonal values for wetland performance, seasons were assigned months as follows: SPRING = February, March, April; SUMMER - May, June, July; FALL - August, September, October; WINTER - November, December, January. The analysis period for which the following summaries are presented began May 1991 (beginning of Summer season) and ended with May 1994 (end of Spring season). Data from monitoring of the original

three parallel wetland cells follows directly. Results that include Cell 4 in series with Cell 1 are detailed in a later section.

4. RESULTS AND DISCUSSION

A. PARALLEL CONSTRUCTED WETLAND CELLS

Measured parameters varied with season and as the system matured (Table 4). Overall reductions of individual parameters, calculated from mean inflow and outflow measurements over the duration of the study, can be compared using Figure 2. Average rainfall for the study area is 127 cm/yr. Precipitation for the first sampling year (May 1991-May 1992) was slightly less, at 101 cm; it was 132 cm for the second sampling year; and rainfall was highest during the third year, totaling 162 cm. Increasing rainfall amounts through the study period could affect interpretations of seasonal and long-term wetland functioning. Individual rainfall events (Figure 3) resulted in temporarily increased discharge from the cells, turbulence, and dilution. Fluctuations in rainfall, variability in waste production, and weather conditions also influenced water depth in the anaerobic lagoon (Figure 4).

Inflow rates to the cells for most of the study period were targeted at 1.0 liters per minute. Actual inflows fell between 0.75 and 1.25 L/min at 84% of our sampling visits. As noted in the methods section above, the wetland cells did not discharge continually. There was zero discharge from the system at 43% of visists to the site. Outflow was observed at 103 out of 181 sampling visits (57% frequency). Of these 103 discharge observations, 57 (55%) were at a rate of less than 0.75 L/min, and 83 (81%) at less than 1.25 L/min (Table 3). Discharges in excess of 1.0 L/min were always associated with rainfall events except during the initial high inflow phase of the project. When no outflow occurred, water samples and measurements were taken after tilting the outflow standpipe until discharge resulted, and the pipe was flushed. This allowed within cell reduction efficiencies to be calculated without the necessity of outflow.

Temperatures at outflows from the cells were 10.9% lower than at inflow stations because of shading by wetland plants and the shallow depth of water within the wetland cells. This was most evident during winter when outflow water temperatures averaged 21% lower than inflow temperatures. Summer temperature reductions averaged 8%. Inflow station extremes ranged from 5.4 to 30.3° C (mean = 17.8). Outflows ranged from 1.5 to 27.3° C (mean = 15.9). Seasonal reduction in temperature is shown in Figure 5.

Conductivity decreased 28.5% with passage through the constructed wetland cells. Greatest reductions occurred during the winter and spring seasons (Figure 6). Reductions increased each year of the study to a peak during spring of 1994 at 44%. Conductivity (Figure 6a) varied from 28 to 773 μmhos/cm at inflows (mean = 343). Outflow conductivity ranged from 103 to 785 μmhos/cm (mean = 245).

Dissolved oxygen concentrations decreased by nearly half (48.8%) when passed through the wetland cells. Increases were measured only during the initial three months of operation (Figure 7). Reduced oxygen levels were attributable to biochemical oxygen demand, bacterial consumption (and nitrification), and duckweed which quickly colonized open water surface. Measurements during the study period ranged from 0.03 to 14.2 (mean = 3.6)

mg/L for inflow stations, and from 0.03 to 7.3 (mean = 1.9) mg/L at outflows in the reducing environment (Figure 7a).

A small (9.9%) decrease in pH was observed for water flowing through the wetland cells. Inflow values for pH (Figure 8a) ranged from 5.7 to 8.5 (mean = 7.0). Outflow values ranged from 5.7 to 7.4 (mean = 6.3). Seasonal reduction percentages for pH were fairly uniform throughout most of the study (Figure 8).

Redox potential in the wetland cells increased an average of 137%. Inflow station measurements (Figure 9a) ranged from (-)259 to (+)311 mV with a mean value of (-)48.39 mV. Outflow measurements ranged from (-)270 to (+)395 mV with a mean of (+)18 mV. Research by Rogers et al. (1991) suggested that increased redox potential in wetland waste treatment systems is due to plant presence, while a decrease in redox occurs in unplanted systems. Though mean values at our site showed an overall increase, values varied widely during the study (Figure 9).

Dissolved solids removal was low (21.8%), while suspended solids removal was relatively high at 60.5%. Total solids were reduced by 31.6% during the three year evaluation (Figure 2). Figures 10, 11, and 12 show seasonal reductions in the solids components during the study. Suspended solids reduction in the wetland cells exhibited distinct seasonal changes linked to plant growth/senescence and plant biomass accumulation/decay (Figure 12). Since much of the suspended solids contained in the waste settled in the lagoon, dissolved solids were the major component entering the wetland. Dissolved solids concentrations during the study varied from 72 to 573 mg/L (mean = 364) at inflow stations, and from 60 to 554 mg/L (mean = 285) at outflows. Suspended solids ranged from 0.0 to 466 mg/L (mean = 122) at inflows and 0.0 to 332 mg/L at outflows (mean = 49). Total solids at inflows (Figure 12a) ranged from 176 to 749 mg/L (mean = 484), and at outflows from 149 to 605 mg/L (mean = 331).

Total phosphorus (TP) removal averaged 53.2% for the three year study period. Removal efficiencies climbed from slightly above 50% during the initial season of operation to near 85% after 9 months of system operation. Trap efficiency declined over the next 6 months to 44% removal (summer, 1992). Thereafter, phosphorus exhibited only moderate removal efficiencies (Figure 13). Inflow TP concentrations (Figure 13a) ranged from a minimum of 1.3 mg/L to a maximum of 69.0 mg/L (mean = 15.9). Outflow concentrations ranged from 0.2 to 22.8 mg/L (mean = 7.4). Principal phosphorus removal mechanisms were probably precipitation and adsorption to sediments. Plant uptake accounted for some removal. If plant removal had been a major uptake mechanism, reduction efficiency would not have declined drastically during the study. Spangler, et al. (1976) found 30 to 66 percent of the total phosphorus in bulrush wetland cells was associated with substrate. Phosphorus is immobilized in organic materials and saturation is reached rapidly (Hammer and Kadlec, 1983). Dolan et al. (1981) discussed phosphorous dynamics in a Florida marsh receiving treated wastewater, and Jones and Lee (1980) evaluated wetlands based phosphorus control for eutrophic waters.

Filterable ortho-phosphorus (FOP) removal efficiency averaged 42.4%, somewhat lower than that for total phosphorus. FOP trapping by the system was near 70% during the initial season of operation and peaked at 85% during the second season. Trapping efficiency declined nearly linearly from that point during the next 12 months to 31% in fall 1992, and averaged 37% afterward (Figure 14). Inflow concentrations (Figure 14a) varied from 0.9 to 24 mg/L

(mean =9.6). Outflows had a low of 0.1 mg/L and high of 15.5 mg/L (mean = 5.5).

Ammonia nitrogen reduction by the wetland system averaged 81.6% overall. Reductions exceeded 90% during the first year of operation, then declined to an average of 81% for the next 5 seasons of the study (summer 1992 through summer 1993). Removal efficiency exceeded 90% again in fall 1993. Reduction then declined to 57% during the next season (winter 1993) and was 65% the final season of the study period (spring 1994) (Figure 15). Ammonia nitrogen concentrations entering the wetland cells (Figure 15a) varied from a low of 0.1 mg/L to a high of 30.8 mg/L (mean = 7.0). Minimum outflowing concentrations reached undetectable levels (<0.01 mg/L) while the maximum outflow concentration measured was 10.8 mg/L (mean = 0.1).

Nitrate nitrogen concentrations entering and leaving the wetland treatment system were low (means = 0.09 and 0.1 mg/L, respectively). Concentrations indicated a net export of nitrate 14.4% higher than inflow, though actual concentrations were nearly negligible. Inflow and outflow concentrations were not expressive of the massive ammonia nitrogen to nitrate nitrogen conversion that occurred within the cells. Export of nitrates was influenced almost totally by that transformation. Seasonal nitrate-N processing began with a 28% average reduction for the first two seasons of treatment, followed by two seasons of 270% export. The system then fluctuated between net reduction and net export during the following 15 months (summer 1992 through summer 1993, averaging 5% reduction overall), before exhibiting > 50% reduction in nitrate-N for the last three seasons of the study (fall 1993 through spring 1994) (Figure 16). Inflow nitrate nitrogen (Figure 16a) ranged from undetectable (<0.01 mg/L) to 0.9 mg/L. Outflow concentrations also ranged from undetectable levels to 3.3 mg/L.

Five-day carbonaceous biochemical oxygen demand (BOD) was reduced consistently by about 80% following the first season of operation (Figure 17) in which there was only a 42% reduction (overall 74.6% reduction). BOD for inflow stations (Figure 17a) averaged 35.1 mg/L (minimum = 9.7, maximum = 80), while outflow stations averaged only 8.9 mg/L (minimum = 0.3, maximum = 48).

Total chlorophyll was also reduced by about 75% (78.8%), though with more seasonal fluctuation (Figure 18) than seen for BOD. Mean inflow concentration was 306 mg/L, with a minimum of <0.01 and a maximum of 1505 mg/L total chlorophyll (Figure 18a). Outflows had a mean of 64 mg/L, a minimum of 1 mg/L and a maximum of 759 mg/L. Inflowing chlorophyll was reduced because of settling and flocculation. In-cell production was minimal because of plant shading.

Coliform bacteria were abundant in pre-treatment lagoon wastewater; yet our data showed there was an 89% reduction in total coliforms with passage through the wetland cells. Inflow concentrations had a mean of 14525 colony forming units (CFU)/100 ml, with a minimum of 40 and a maximum of 101000 CFU/100 ml. Outflow mean concentration was 1585 CFU/100 ml, with a minimum observed of 20 and a maximum of 19700 CFU/100 ml. (This information excludes individual tests where sample dilution resulted in extinction of coliform bacteria and resultant lack of colony forming units.)

Chemical oxygen demand, the oxygen equivalent of the organic matter that can be oxidized by a strong chemical oxidant, was measured on a quarterly schedule. Average inflow demand was 263 mg/L, while outflow demand was only 96 mg/L, resulting in a mean reduction in COD of 63% with passage through the wetland cells (Table 5).

B. RESULTS FROM ADDITION OF CELL 4

A single additional cell of the same dimensions as an original cell was added in series to Cell 1 during Summer 1991 (Fig. 1). This cell, Cell 4, received effluent from Cell 1 only, and served as an experimental polishing cell. Bulrush cuttings planted in the fall of 1991 failed to grow, probably due to subsequent inundation by heavy rainfalls. The cell was re-planted in Spring 1992 (late April /early May) with rhizome cuttings at one meter intervals. By early June, 1992, plantings had expanded as healthy spreading clumps. By early August they formed a nearly continuous stand within the cell. In late October, 1992, the rushes in Cell 4 still maintained a healthy dark-green color. Natural senescence occurred after freezing temperatures occurred in early December.

Bulrush re-growth in the spring of 1993 occurred in mid-March; growth was evenly distributed throughout the cell. The stand flowered in July. The bulrushes in Cell 4 remained healthy through September and began showing some signs of natural seasonal decline during October. Stems browned and began decomposition by mid-December. Re-appearance of bulrushes in Cell 4 occurred during mid-March 1994. By May, 1994, a sparse stand of new stems was visible throughout the cell.

When compared to mean changes of parameters in the original three cells, Cell 4, acting as an additional treatment cell, produced the following notable changes in water quality. Conductivity produced an added 23% reduction for a total reduction of over 51% from inflow values at Cell 1. Dissolved oxygen concentrations in Cell 4 increased relative to Cell 1 outflow, yet did not equal concentrations entering the wetland cells from the lagoon. This increase in oxygen resulted in an overall 28% reduction of DO, as opposed to a 48% average reduction that occurred in the three original cells. Likewise, pH values increased as water flowed through Cell 4, as opposed to decrease in the original cells, but again not reaching original inflow values (5% decrease with Cell 4 included vs. 10% average decrease in original cells alone). Total solids decreased an additional 20%, for a total reduction of >51% because of dissolved solids trapping. There was little change in suspended solids concentrations in Cell 4.

Filterable ortho-phosphorus concentrations declined an added 37%, and total phosphorus declined an additional 23% in Cell 4. This added trapping was similar to initial phosphorus trapping in the first three cells. Ammonia-nitrogen concentrations declined an additional 13% over the average original cell reduction of 82%. Nitrate-nitrogen concentrations at outflow from Cell 4 were 52% lower than inflow at Cell 1, negating the increase of nitrate-nitrogen observed in the original cells (though, again, actual concentrations were very low, with mean values of 0.10 mg/L or less for all inflow and outflow stations). Total chlorophyll concentrations and BOD were 9% less when Cell 4 was used. Coliform bacteria concentrations were relatively unchanged.

C. IN-CELL PROCESSING

Because of the length:width ratio, our constructed wetland cells were assumed to have plug flow (Reed et al., 1988). A dye study during the second year of the project confirmed this to be true.

Monitoring of in-cell processing was accomplished by sampling from three catwalks evenly spaced along the length of one constructed wetland cell (Cell

2). Samples were collected from just above the sediment-water interface along the centerline of the cell using a hand operated Black and Decker company Jack Rabbit™ pump fitted with 1 mm mesh cloth at the hose inflow to preclude larger particulates from entering the sample.

Mean temperature measurements decreased from inflow approximately 2.7°C before reaching station 2A. Measurements within the cell from stations 2A, 2B, and 2C were fairly uniform, but temperatures at outflow from the cell were generally about 0.7°C higher than those in the interior of the cell (Figure 19). Lower temperatures within the cell were attributed to shading from the cultivated bulrush and invasive duckweed.

Conductivity values declined nearly linearly from inflow toward discharge but plateaued near the rear of the cell (Figure 20). The total decrease was approximately 112 μmhos/cm.

Dissolved oxygen concentrations did not display a linear decrease, but rather declined abruptly after water entered the cell (Figure 21). The mean decrease from cell inflow to the nearest sampling site, 2A, was 2.3 mg/L, and to cell outflow was 1.9 mg/L, showing that a slight increase in oxygen concentration occurred in the outflow region of the cell after the initial oxygen depletion. The initial decrease in the front portion of the cell probably resulted from BOD, microbial consumption as incoming nutrients were assimilated or nitrified, and elimination of photosynthetic production of oxygen because of exclusion of sunlight by plant shading. A gradual, slight increase occurred thereafter, but discharge concentrations were still nearly half those at inflow.

Wastewater entering the constructed wetland cell had a mean pH which was nearly neutral (7.0 units); pH declined by more than half a unit at site 2A. Modest decreases were observed until discharge (Figure 22). The mechanism causing H^+ ion release was not isolated, but may have been linked to nitrification occurring in oxygenated regions of the wetland cells. Support of this hypothesis can be seen by comparing mean oxygen concentration and pH value at sites in Cell 2 (Figures 21 and 22, repectively). Also, see further discussion of nitrogen transformations below.

Total solids were reduced 32% overall during passage through the cell although concentrations initially increased over 130 mg/L from inflow to site 2A (Figure 23). This increase was not attributed to dissolved solids (Figure 24), which decreased gradually to outflow, but was from suspended solids which peaked at site 2A (Figure 25). This suspended solids peak was nearly 165 mg/L above inflow concentrations, and levels remained above inflow concentrations at both site 2B and 2C. Concentrations decreased to below inflow levels before exiting the cell. Overall reduction of suspended solids was 56%. This indicates that the introduced and in-cell generated suspended solids were trapped fairly effectively.

Filterable ortho-phosphorus (Figure 26) and total phosphorus (Figure 27) decreased similarly through the cell in a nearly linear manner, but with a greater proportion of ortho-phosphorus leaving the cell (only 44% trapping versus 55% trapping for total phosphorus). The greater retention seen for total phosphorus was because it contained "non-bioavailable" phosphorus which could be trapped in sediment and soils, while ortho-phosphorus was cycled biologically through the cell.

Mean ammonia nitrogen concentrations decreased linearly from inflow to station 2B (midpoint of the cell), then began to plateau to an outflow concentration less than one sixth that of inflow (Figure 28). Nitrate

nitrogen began at low concentrations (<0.1 mg/L), but concentrations increased sharply in the first portion of the cell to nearly 2.5 times that of inflow as ammonia was converted to nitrate (Figure 29). It then declined steadily as wastewater passed through the cell, until discharge, at which point the concentration was below inflow levels; nitrate uptake showed cell to cell variation which resulted in net uptake or export, depending on conversion.

Nitrogen transformations in wetlands are often complex and are accomplished by the presence of specific bacteria. A quantitative study of nitrogen processing and transformation in Cell 2 is still being completed. It includes spatial enumeration of nitrogen compound concentrations and nitrogen-transforming bacteria. There are several major nitrogen transformations that occur in wetlands. Ammonification is the reduction of organic nitrogen to ammonium (NH_4^+) by microorganisms in the substrate and water column. This process is prone to anoxic conditions. NH_4^+ can be used by plants and is important due to the rapid breakdown of nitrate (NO_3^-) under anaerobic conditions making NO_3^- less available to plants (Chan, et al., 1982). Since ammonium is an ion, it can also readily lose a hydrogen to convert to ammonia (NH_3). Volatilization occurs when NH_3 is lost at the water-air interface. However, volatilization depends on a slightly alkaline pH (8.0) which limits this process. Nitrification refers to oxidation of an NH form to a nitrogen oxide in an oxygenated environment, principally in the water column or surface but can be at the root zone. In the presence of oxygen, the bacteria *Nitrosomonas* converts NH_4^+ to nitrite (NO_2^-) and *Nitrobacter* converts NO_2^- to NO_3^-. Nitrification may partially depend on aquatic plants which provide substrate and an oxygenated environment for these nitrifying bacteria. Denitrification refers to the dissimilar reduction of one or both of the nitrogen oxides to gaseous oxides [nitric (NO) and nitrous oxide (N_2O)] which then may be converted to gaseous nitrogen (N_2) (Knowles, 1982). Denitrification occurs under anaerobic conditions where one of the nitrogen oxides act as a terminal electron acceptor in the absence of oxygen. This is an important process for nitrogen removal from many wetlands and likely was a major transformation in our cells because of low oxygen conditions. Studies on the enzymes that catalyze the reactions of this process are also being conducted using bacteria isolated from our study sites.

Ninety-seven bacterial isolates were obtained from several points in Cell 2 for detailed study. The isolates were put onto selective anaerobic media [NO_3 and Fe(III) reducing medium] and tested for reducing capabilities. The results were as follows: 22 isolates could reduce nitrate; 36 could reduce Fe; 3 reduced nitrate to a gas species (denitrication); 15 could reduce nitrate and also reduce Fe(III); 3 could reduce nitrate to a gas species and also reduce Fe(III); and 18 were neither nitrate nor Fe(III) reducers (other).

There have been few significant studies done on microorganisms having alternative energy conservation schemes. These studies have produced primary evidence which suggests that some organisms with the capacity to utilize Fe(III) as a terminal electron acceptor might have a "related" nitrate reductase enzyme (NR). More specifically, inhibition of Fe(III) reduction may occur in the presence of NO_3. In medium without NO_3, NR mutants produced less Fe(II) than did their wild type homologs (Lovley, 1991). Lovley argues that there is still no direct evidence for the involvement of NR in Fe(III) reduction. He offers such other possibilities as chemical oxidation (NO_2), alternate pathways, and misconstrued data (Lovley, 1991).

It is a reasonable assumption that alternative catabolic schemes offer a competitive advantage to certain organisms. Bacteria have to respond to the wide range of "Diets" available in the subject environment. Competitive inhibition would equal depreciated denitrification in the presence of Fe^{++}. Overall performance of N removal in waste reduction systems would suffer. Further studies regarding nitrate reductase (insoluble) are needed in order to facilitate the determination of the mechanisms of energy conservation in these bacteria.

Mean chlorophyll concentrations decreased sharply (>50%) between inflow and 2A. From that point, they decreased gradually until discharge (Figure 30) for a 75% total reduction in concentration. Shading from bulrushes and duckweed reduced photosynthesis while physical and biological trapping reduced concentrations.

Values for 5-day carbonaceous biochemical oxygen demand decreased more than 50% in the first half of the cell. Little change was measured from 2B to 2C, but a further reduction occurred from 2C to outflow (Figure 31) that resulted in a 76% reduction overall. The small peak observed for BOD near the end of the cell is characteristic of some other constructed wetland treatment systems (Hunt, P.G., and Stone, K.C., personal communication).

Coliform bacteria concentrations declined sharply from inflow to site 2A. After this reduction, however, concentrations remained nearly uniform until outflow (Figure 32), but at levels less than one seventh those of inflow concentrations.

Chemical oxygen demand, like nitrate nitrogen, exhibited a peak after entering the cell (2A). Moderate values were measured further in the cell, and lowest values were monitored at cell discharge.

D. EFFECTS OF MATURATION

No long term temperature trends were evident beyond expected seasonal changes. Temperature dynamics in the constructed wetland cells followed ambient trends (Figure 5a). Cooling was most noticeable during the winter and spring months (Figure 5). Inflow water temperature was kept elevated by the larger water volume retained in the primary settling lagoon.

Conductivity of water entering the cells was highest during summer and fall months when evaporation was high (Figure 6a). Long term reduction of conductivity by wetland cell treatment increased slightly in each winter-spring cycle through the study (Figure 6); inflow values of lagoon water also rose slightly during these seasons. Peak values were highest during 1992 and 1993.

Dissolved oxygen concentrations in inflowing water showed an increasing trend through the study period (Figure 7a). Loss of oxygen within the cells from oxygen demand, however, also increased with time (Figure 7).

The pH of water entering the cells remained nearly uniform (Figure 8a). There was a slight tendency away from acidification in the cells during the final two seasons of monitoring, winter 1993 and spring 1994 (Figure 8).

The mean redox potential of inflow sampling stations was (-)48 mV, but values ranged to in excess of (+)300 mV and below (-)250 mV (Figure 9a). Seasonal changes in redox potential displayed no obvious trend.

We were not able to detect any long term trends for efficiency of removal of solids components. Solids removal by the constructed wetland was usually highest during the spring-summer period (Figures 10, 11, 12), when

inflow values tended to be slightly lower and effluent from the lagoon more concentrated (Figure 12a). This also coincided with seasonal plant growth and maturation.

Filterable ortho-phosphorus trapping efficiency during the first six months of wastewater treatment exceeded 80%. Trapping efficiency declined and stabilized as the cells loaded with phosphorus. Trapping approximated a sustainable efficiency of 37% after 18 months (Figure 14). This trend may be due, in part, to increases in FOP concentrations entering the wetland cells (Figure 14a). Phosphorus seasonal cycles were similar to those of natural wetlands. Processing efficiency declined in midwinter and early spring as phosphorus was released from the system. Results for total phosphorus are similar (Figures 13, 13a).

Ammonia nitrogen trapping efficiency by the wetland declined over time, but most dramatically during the last two seasons of monitoring (Figure 15) although inflow concentrations of ammonia nitrogen during these seasons were relatively low (Figure 15a). Nitrate nitrogen trapping fluctuated widely during the study, often becoming negative and resulting in net export of nitrate from the constructed wetland (Figure 16). Figure 16a displays a slight trend toward an increasing number of "spikes" in nitrate nitrogen concentrations entering the cells. Actual mass of nitrates exported was not significant. Nitrate cycles were directly related to ammonia nitrogen/nitrate transformations.

Inflow values for 5-day carbonaceous oxygen demand varied by over 70 mg/L, often fluctuating greatly from one sampling visit to the next (Figure 17a). Despite these variations, the reduction in BOD load generated by the constructed wetland remained seasonally consistent and high following the initial season of operation through the end of the study (Figure 17).

Concentration of chlorophyll entering the cells varied widely (Figure 18a). After the first season of operation, chlorophyll trapping remained high through most of the study except for two periods of distinctly lower efficiency (Fall 1992 and Summer 1993, Figure 18). The low trapping efficiency during the initial season, Summer 1991, occurred while rushes were first becoming established and not able to shade the water column. In addition, algae-consuming invertebrates were not well established in the wetland cells at this time.

E. CONTAMINANT LOADING

For computing loading rates of pollutants, hydraulic load on individual cells was 1 cm/day (1440 L over 144 m^2 per day). Loading on the constructed wetland for pertinent parameters is given in Table 6. Dissolved solids were the major contributor to total solids load entering the constructed wetland cells since suspended solids in the original waste settled mostly in the anaerobic lagoon pretreatment area. With an average of over 254 kg of solids entering each cell per year, the three parallel constructed wetland cells received over 2280 kg of solids during this study, and trapped approximately 720 kg. Filterable ortho-phosphorus loading averaged 13.8 g/day, over 5.0 kg/year, on each cell. The total amount of FOP entering the cells during the study was 45.4 kg, of which more than 19 kg was retained. Total phosphorus loading to each cell was higher, at over 8.3 kg/year/cell. Total load was 75 kg, of which nearly 40 kg was trapped. Ammonia nitrogen loading averaged 3.7 kg/yr/cell, or 32.9 kg total loading for the study, of which 26.8 kg was

removed. Nitrate nitrogen loading was much lower, at only 0.05 kg/year/cell. Because of ammonia-nitrogen conversion, there was a net nitrate-N export of 0.06 kg for the three year study period. Total chlorophyll input to the constructed wetland cells was over 161 kg/yr/cell. This calculates to 1449 kg which entered the wetland cells; 1142 kg was not discharged. Carbonaceous 5-day biochemical oxygen demand was 18.48 kg/yr/cell, totaling 166.33 kg for the study period. Average reduction of BOD was 74.56%, indicating a net reduction of 124 kg BOD from our wastewater treatment system effluent.

5. OBSERVATIONS AND RECOMMENDATIONS

A. Biomass Removal - Bulrush vegetative growth generally matted after senescence. In many cases mats assisted in forming anaerobic conditions and were impenetrable, preventing renewed spring growth. Harvesting of biomass enhanced growth in Cell 1 and eliminated the matting problem for the short term. However, bulrushes should not be recommended unless some harvesting method is planned. An annual harvest would also reduce the phosphorus which is temporarily bound in plants. Natural wetland studies reveal seasonal export of phosphorus in spring after plant material decays (Spangler, et al. 1976). Our study (Figure 13) exhibited a decline in total phosphorus trapping each spring. Spangler, et al. (1976) also found that a single fall harvest netted greater biomass than several periodic cuttings over the growth season. Gersberg, et al.(1983) recommended annual harvest for improved cell productivity. They also mulched wetlands to add carbon to assist in nitrogen removal. With some species such as cattails, burning excess biomass during the simulated dry part of a hydroperiod may be feasible.

B. Plant spacing - Some authors (Gearheart, 1992) recommend high initial planting density. We initially used a 0.3 m setting on staggered rows for our first plantings. When we planted our 4th cell and replanted bare spots, we used a 1.0 m setting on staggered rows. The 1.0 m setting was satisfactory with *Scirpus validus* because of vigorous rhizome growth.

C. In-cell processing and cell dimensions - Results showed that some contaminants were processed in a linear fashion and that processing was dependent upon cell length. Processing for others was mainly in the first third of the cell. Cell design should be targeted for principal contaminants, and cell size should depend on the worst case processing efficiency. Overdesigning cells so that outflow is not continuous but is seasonal allows for some resemblance of a natural wetland hydroperiod.

D. Maintenance - Properly designed inflow/outflow piping requires routine flushing. Levee maintenance is essential. Multiple cells are highly desired so that a single cell can be isolated for maintenance. With bulrushes, plant biomass becomes a significant problem within three years. Plants must be harvested or biomass otherwise removed. We conducted two biomass removals. Both exhibited some degree of success although each had difficulties. Mechanical removal of dead material successfully allowed new shoots to sprout, but it was labor intensive. We also drained one cell and burned dead material. This method required constructing a sump and pumping water from the cell for 4 days. Burning may be more successful with species like cattails which produce clumpy, easily burnable biomass.

E. Constructed wetlands represent a low initial cost/low maintenance method for treating some animal wastes. Table 7 compares several animal waste studies. All show good trapping efficiency for ammonia nitrogen, BOD, and coliforms.

6. CONCLUSIONS

Three parallel wetland cells, planted to giant bulrush, were evaluated for 36 months while receiving wastewater via a primary settling lagoon from a <100 cow dairy operation. Results from these three original cells showed best reductions in coliforms, BOD, chlorophyll and ammonia nitrogen, the potential contaminants of concern. Study length allowed for some evaluation of cell maturation. Initial phosphorus and nitrogen processing was quite high. However, when cells became loaded with these nutrients, efficiencies stabilized at lower rates. Seasonal variations were evident, but cells were functional continuously. Effectively doubling the cell length by adding a fourth cell allowed for 24 months of additional comparison. Greatest changes from additional length were in nutrient removal and dissolved oxygen improvement. Cell size should be based on most effective treatment of targeted contaminants. The major negative factor associated with bulrushes was build up of biomass. Removal of decaying biomass was essential for annual plant emergence from rhizomes. Constructed wetland cells represent an alternate method of processing some agricultural wastes, but, as our study showed, individual cell variability and seasonal/long-term trends make operation challenging.

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TABLE 1. NRCS Calculated Data For Loading Estimates

RAINFALL RUNOFF AREA

ROOF AND CONCRETE	351	sq. meters
ANAEROBIC LAGOON	2132	sq. meters
WETLAND CELLS (3)	432	sq. meters

DAIRY WASTE PRODUCTION

(Based upon 100 cow dairy herd)	10336	Liters / day

TABLE 2. Parameters Monitored

Abbreviations in parentheses

STAFF GAGE	(GAGE)
RAIN GAGE	(RAIN)
$CBOD_5$	(BOD)
COLIFORMS	(COL)
TEMPERATURE	(TEMP)
CONDUCTIVITY	(COND)
DISSOLVED OXYGEN	(DO)
pH	(PH)
REDOX	(RED)
CELL INFLOW/OUTFLOW	(Q)
TOTAL SOLIDS	(TS)
SUSPENDED SOLIDS	(SS)
DISSOLVED SOLIDS	(DS)
CHLOROPHYLL	(CHL)
FILTERABLE ORTHO PHOSPHORUS	(FOP)
TOTAL PHOSPHORUS	(TP)
NITRATE-NITROGEN	(NO_3)
AMMONIA-NITROGEN	(NH3)
CHEMICAL OXYGEN DEMAND	(COD) quarterly

TABLE 3. Bin Summary of Wetland Cell Inflow and Outflow (Q)

Range (Liters/minute)	Frequency	Percent	Cumulative Frequency	Cumulative Percent
		CELL 1, 2, 3 INFLOWS		
Zero	5	3%	5	3%
0.001 - 0.750	18	10%	23	13%
0.751 - 1.250	153	84%	176	97%
1.251 - 1.750	2	1%	178	98%
1.751 - 2.250	2	1%	180	99%
> 2.250	1	1%	181	100%
		CELL 1, 2, 3 OUTFLOWS		
Zero	78	48%	78	43%
0.001 - 0.750	57	31%	135	75%
0.751 - 1.250	26	14%	161	89%
1.251 - 1.750	7	4%	168	93%
1.751 - 2.250	1	1%	169	93%
> 2.250	12	7%	181	100%
		CELL 4 OUTFLOWS		
Zero	27	61%	27	61%
0.001 - 0.750	9	20%	36	82%
0.751 - 1.250	1	2%	37	84%
1.251 - 1.750	1	2%	38	86%
1.751 - 2.250	1	2%	39	89%
> 2.250	5	11%	44	100%

TABLE 4. Mean Seasonal Reductions by Parameter.

	Temp	Cond	DO	PH	RED	TS	DS	SS	FOP	TP	NH_3	NO_3	CHL	BOD	COL
1991															
Summer	3%	17%	-7%	9%	153%	13%	9%	22%	69%	53%	92%	33%	30%	42%	74%
Fall	18%	23%	33%	8%	74%	27%	14%	63%	85%	67%	92%	24%	88%	77%	86%
Winter	23%	29%	28%	13%	-103%	33%	26%	58%	71%	87%	90%	-261%	85%	80%	99%
1992															
Spring	15%	31%	50%	11%	126%	40%	26%	74%	56%	81%	96%	-278%	86%	82%	99%
Summer	11%	27%	63%	12%	41%	42%	22%	79%	44%	44%	80%	40%	94%	80%	96%
Fall	10%	18%	19%	12%	59%	27%	26%	26%	31%	42%	85%	31%	59%	77%	37%
Winter	17%	38%	47%	10%	634%	37%	29%	63%	26%	29%	76%	-6%	86%	82%	99%
1993															
Spring	15%	36%	45%	9%	443%	41%	27%	79%	36%	41%	86%	32%	82%	83%	96%
Summer	9%	9%	59%	11%	-377%	31%	20%	53%	23%	28%	79%	-79%	63%	78%	85%
Fall	2%	25%	40%	8%	-217%	27%	24%	39%	37%	33%	93%	58%	85%	82%	NA
Winter	24%	31%	84%	5%	-42%	27%	1%	85%	36%	45%	57%	87%	97%	84%	62%
1994															
Spring	10%	44%	51%	7%	7%	37%	37%	51%	37%	43%	65%	56%	80%	81%	NA

TABLE 5. Chemical oxygen Demand by Site and Date.

VALUES

Site	5/22/91	8-5-91	11-4-91	6-2-92	10-6-92	2-1-93	6-1-93	10-1-93	1-24-94	Average
1i	144	145	290	445	210	328	185	243	194	243
1o	98	93	58	168	NA	124	94	49	88	96
2i	240	NA	410	355	220	315	200	155	175	259
2a	115	642	122	603	124	228	418	218	193	296
2b	136	NA	97	290	263	203	300	123	90	188
2c	123	663	89	210	119	147	354	173	115	221
2o	133	NA	52	105	88	113	198	49	86	103
3i	225	NA	300	445	225	298	NA	230	NA	287
3o	102	NA	50	114	119	68	NA	83	NA	89
4o	NA	NA	NA	197	NA	50	83	54	34	83
LG	NA	608	260	937	245	310	203	204	125	361

REDUCTIONS

Cell 1	32%	36%	80%	62%	NA	62%	49%	80%	55%	60%
Cell 2	45%	NA	87%	70%	60%	64%	1%	68%	51%	60%
Cell 3	55%	NA	83%	74%	47%	77%	NA	64%	NA	69%
Cell 4	NA	NA	NA	-18%	NA	60%	12%	-10%	62%	14%
1i-4o	NA	NA	NA	56%	NA	85%	55%	78%	83%	66%
Avg-1,2,3	44%	36%	84%	69%	54%	68%	25%	71%	53%	63%

TABLE 6. Summary of Contaminant Loading on Alan Scott Farm Constructed Wetland

Amount	TS	DS	SS	FOP	TP	NH3	NO3	CHL	BOD
kg/year/cell	254.42	191.65	64.04	5.04	8.34	3.66	0.05	161.0	18.48
kg/all cells/study	2289.80	1724.84	576.37	45.35	75.10	32.91	0.42	1449.05	166.33
retained kg/all cells/study	722.43	373.77	346.63	19.21	39.93	26.84	-0.06	1142.40	124.02

TABLE 7. Comparison of contaminant reduction by constructed wetland cells (regardless of age or size).

Study	Site	Animal	Plant	NH_3	NO_3	COD	BOD	TP	S. Solids	Coliform
Cooper, et al., 1995[1]	MS	Cattle	bulrush	82	-14	63	74	53	60	89
Cooper, et al., 1995[2]	MS	Cattle	bulrush	94	52		83	76	62	79
Payne, et al., 1992	AL	Swine	various	90.3		65.1	82	72	79	>90
Spangler, et al.,1976[3]	WI	Municipal	Bulrush			89	98	84		
Spangler, et al.,1996[4]	WI	Municipal	Cattail			35	90	67	78	97
Kumar and Garde, 1990	India	Municipal	Hyacinth	79		95	96	69		

1 Reduction in 1st cell in series alone.
2 Reduction in 2 cells in series, i.e. twice the length of one.
3 Maximum retention reduction (5 day) in greenhouse studies.
4 Natural marsh.

FIGURES

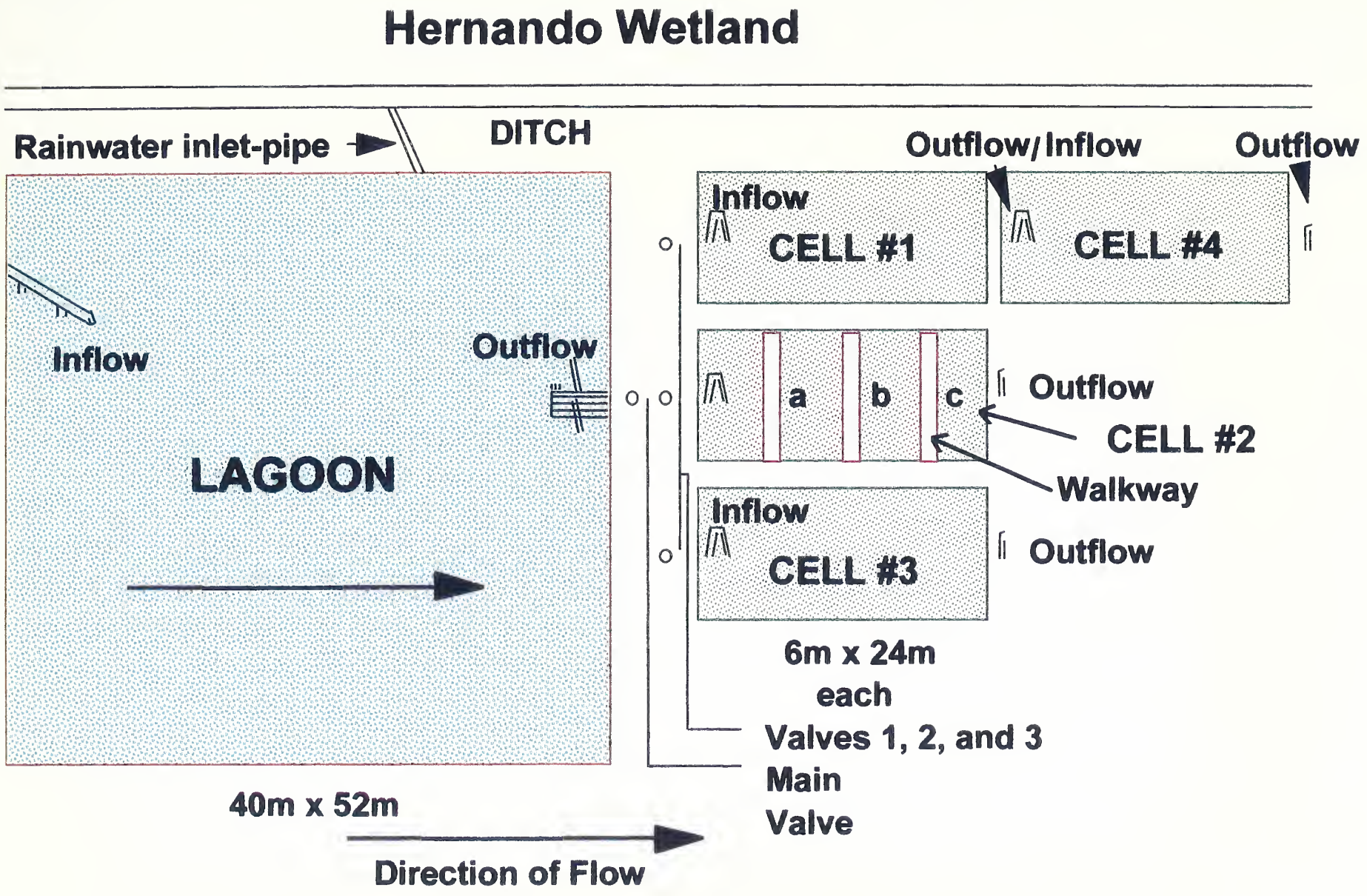

Figure 1. Drawing of lagoon\wetland cell construction at Hernando Wetland on Alan Scott Farm, DeSoto County, Mississippi, USA.

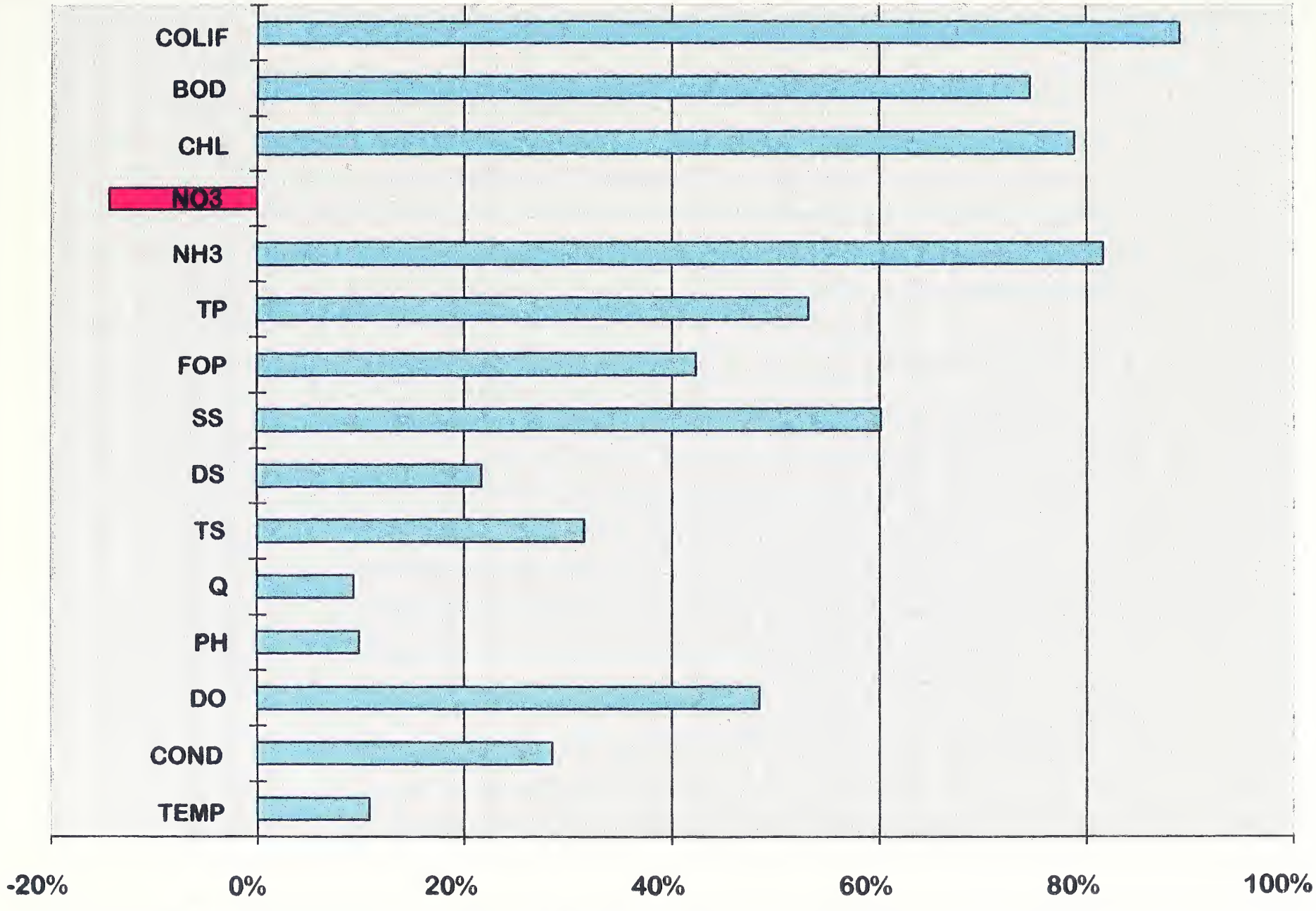

Figure 2. Mean percent reduction of contaminants by using constructed wetland.

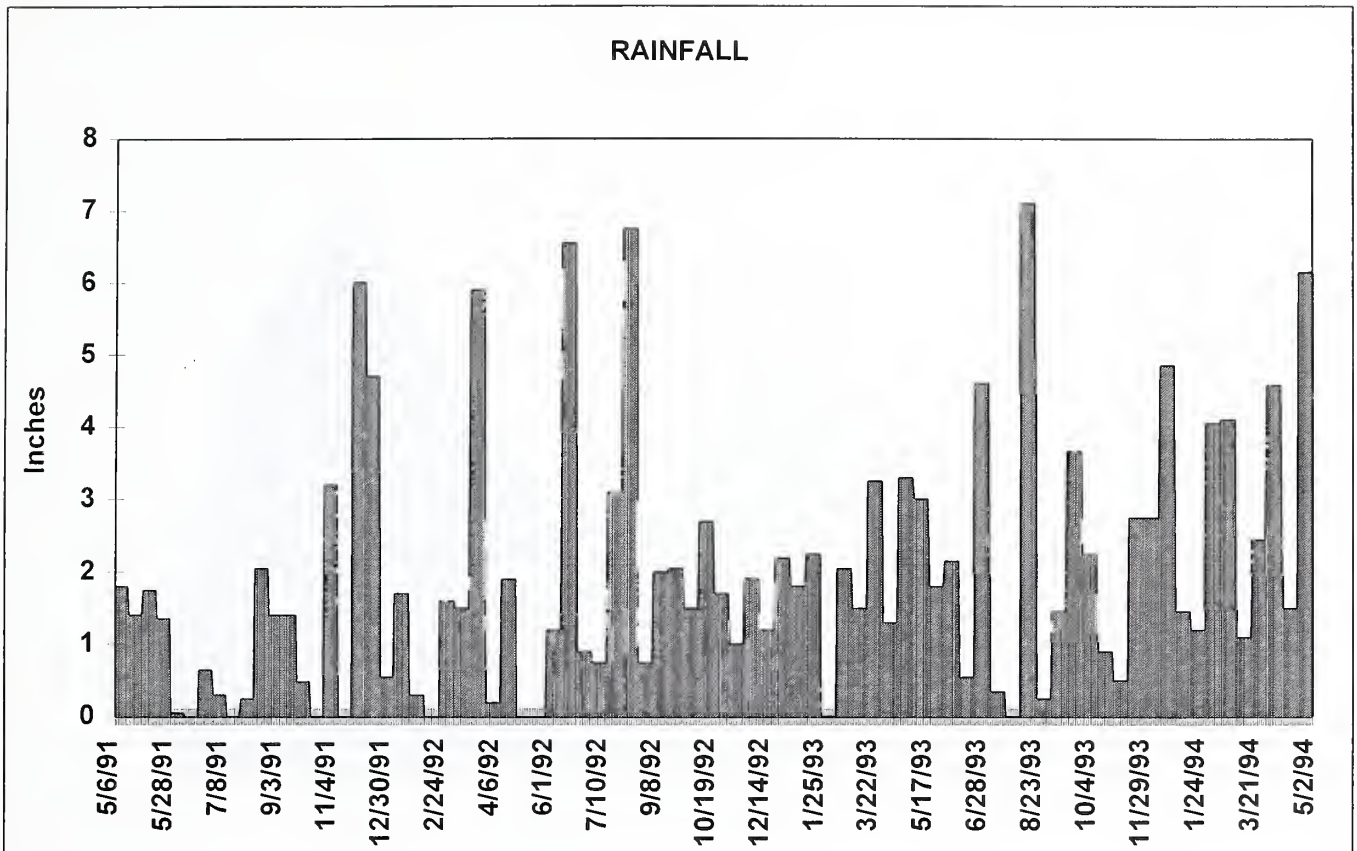

Figure 3. Rainfall amounts by date.

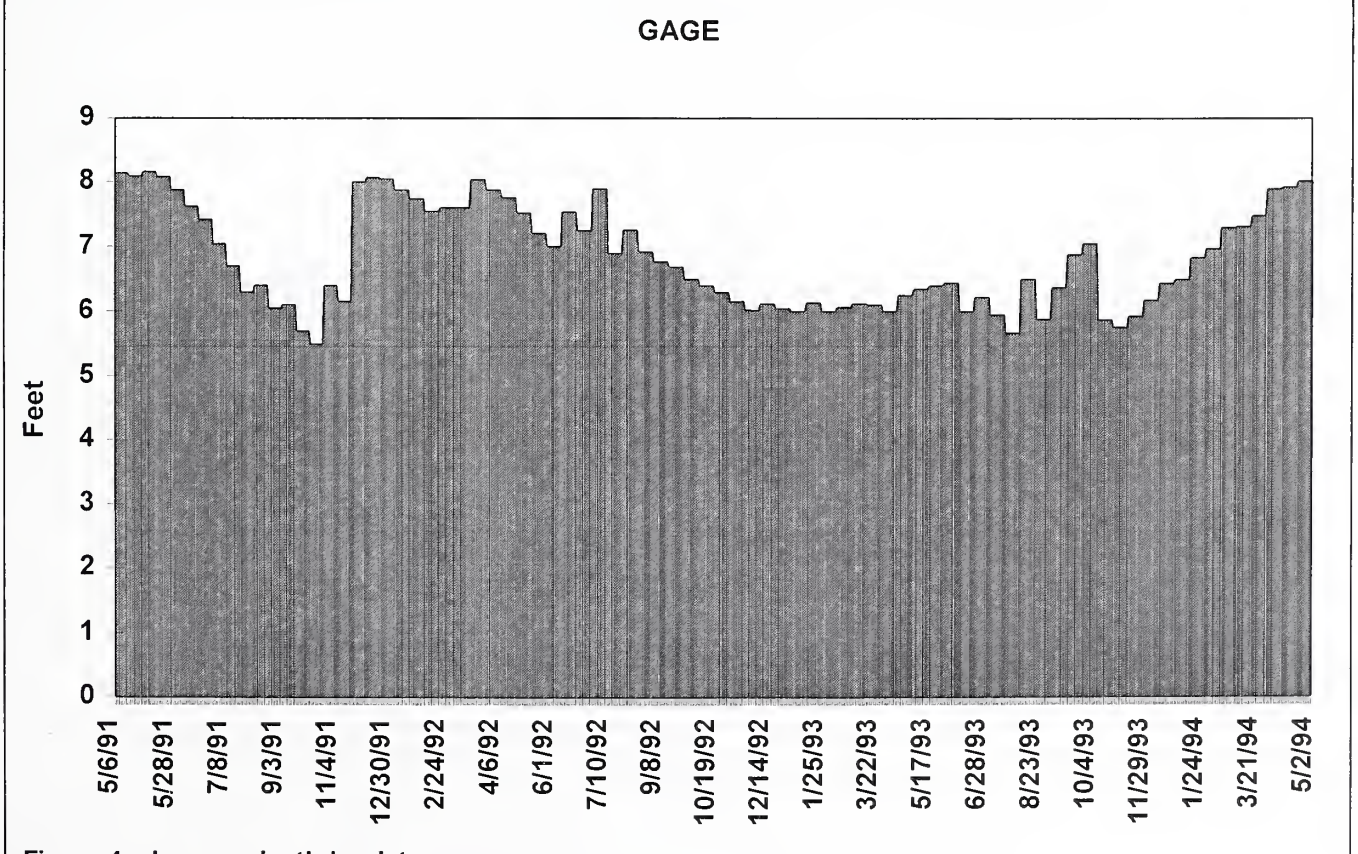

Figure 4. Lagoon depth by date.

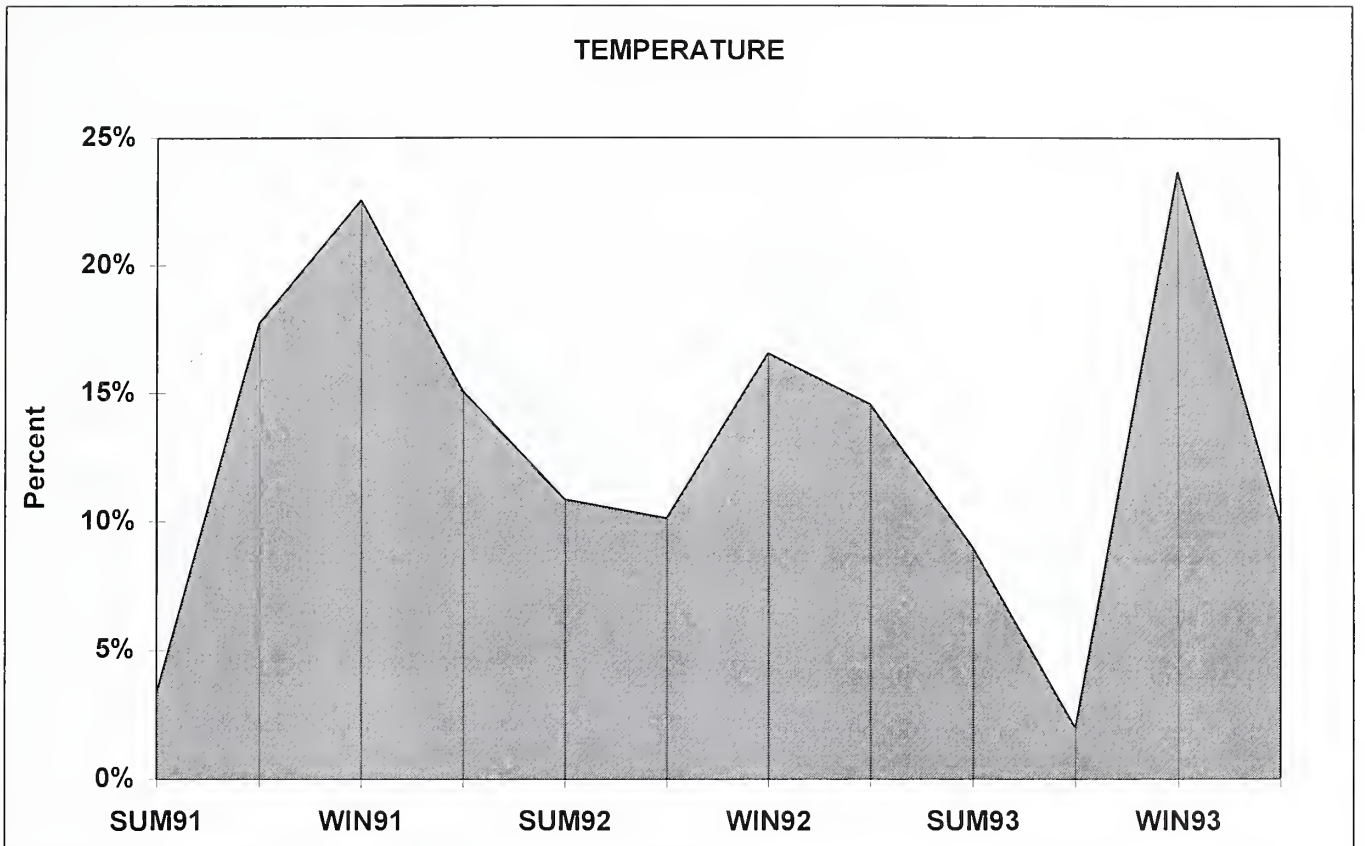

Figure 5. Temperature reduction in wetland by season.

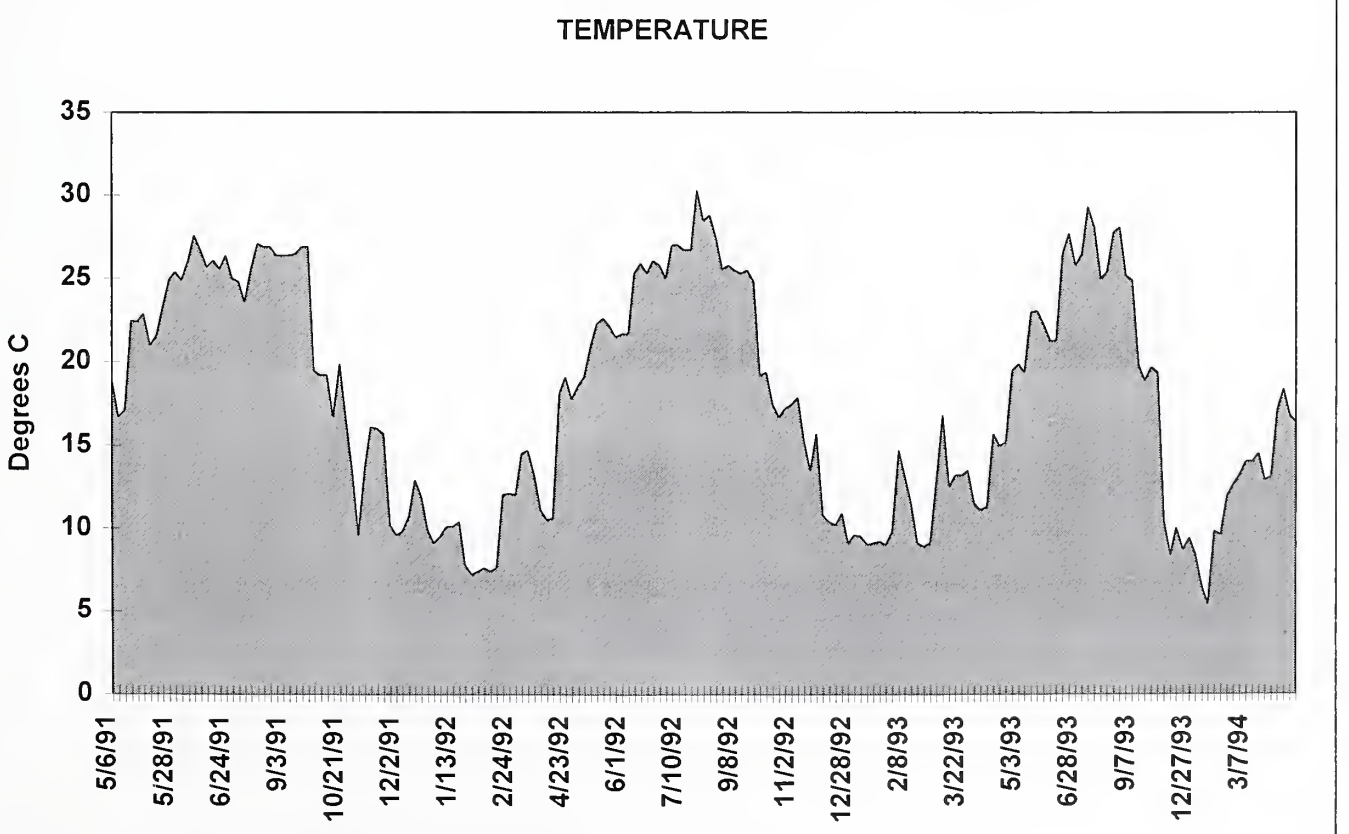

Figure 5a. Inflow temperature values by date.

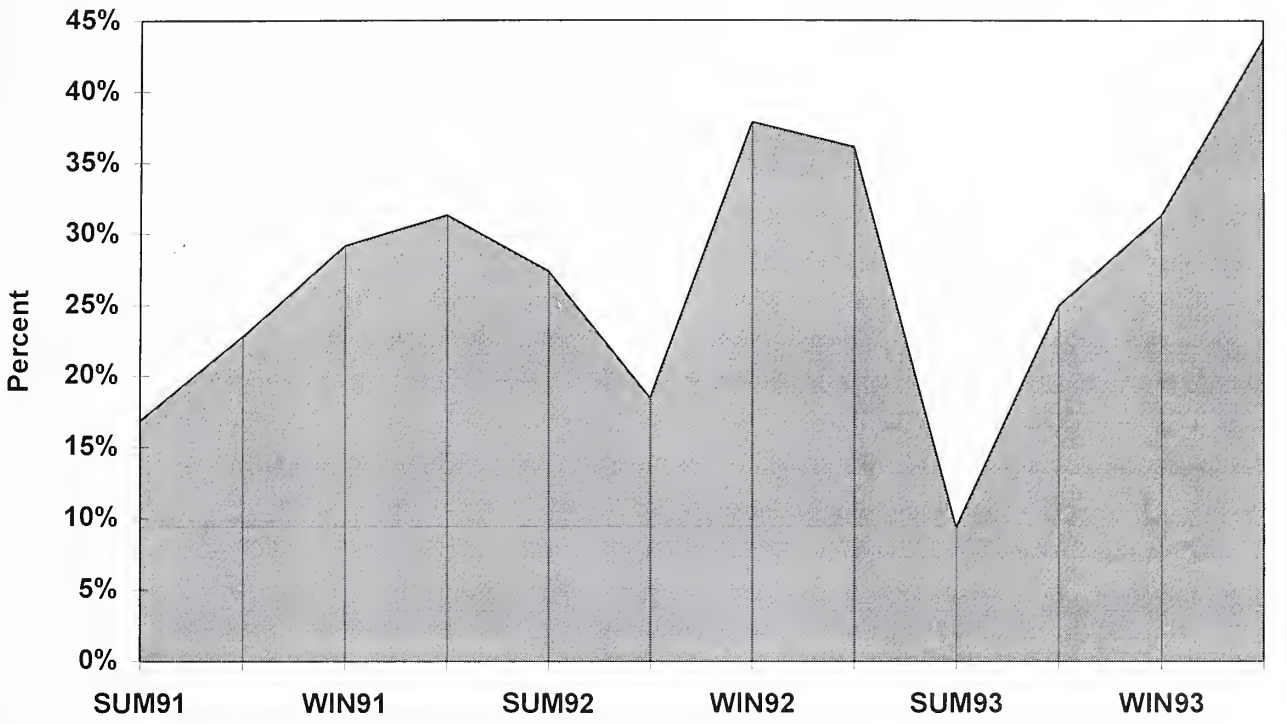

Figure 6. Conductivity reduction in wetland by season.

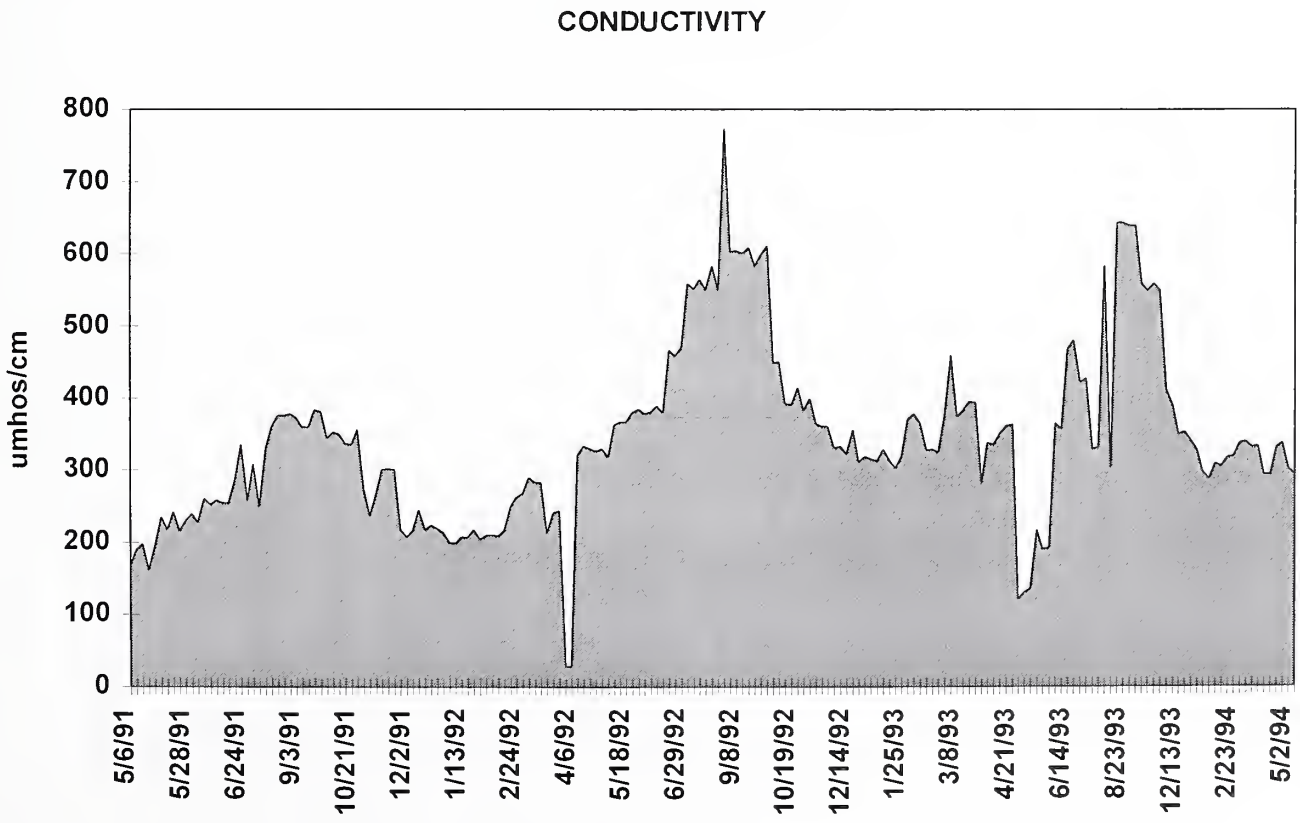

Figure 6a. Inflow conductivity values by date.

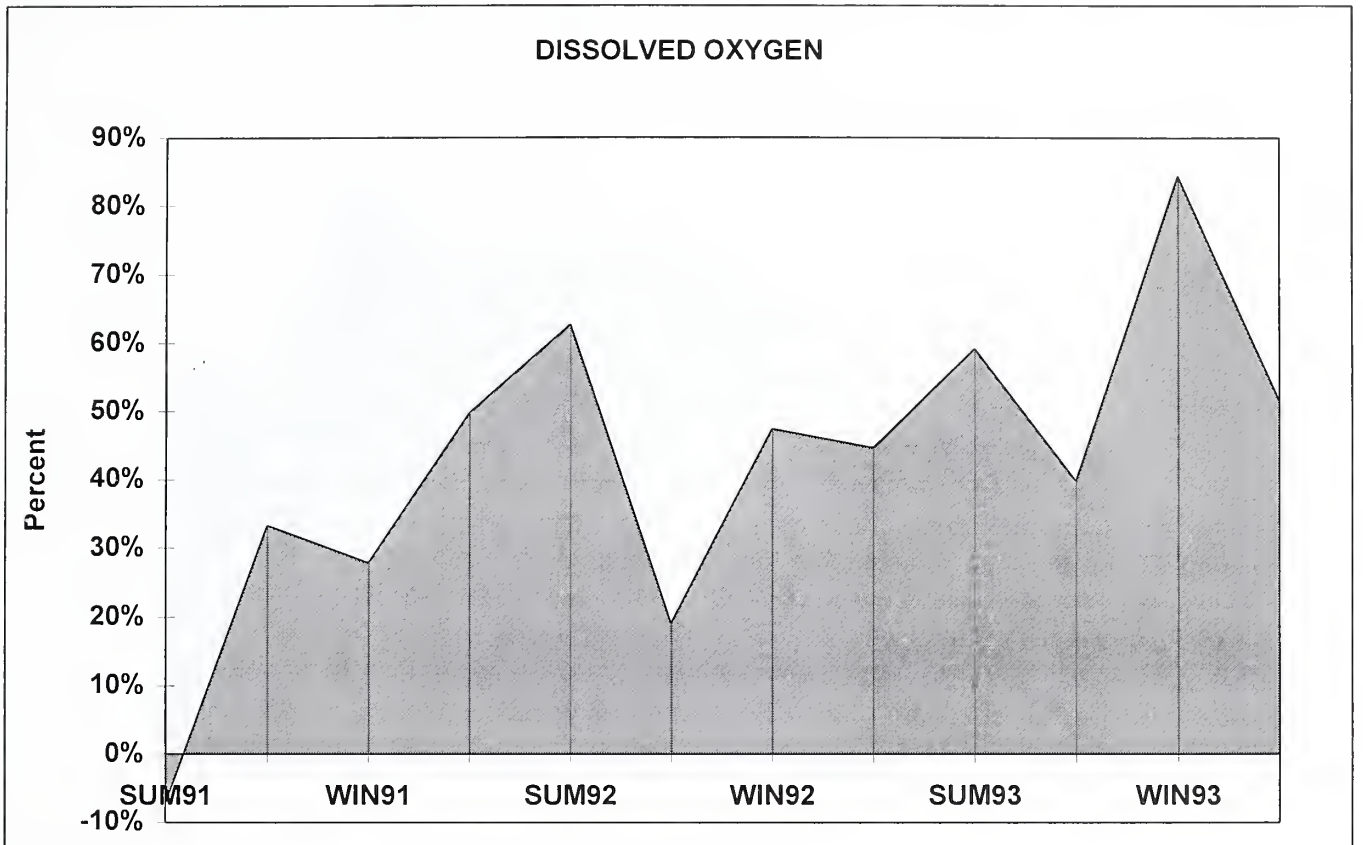

Figure 7. Dissolved oxygen reduction in wetland by season.

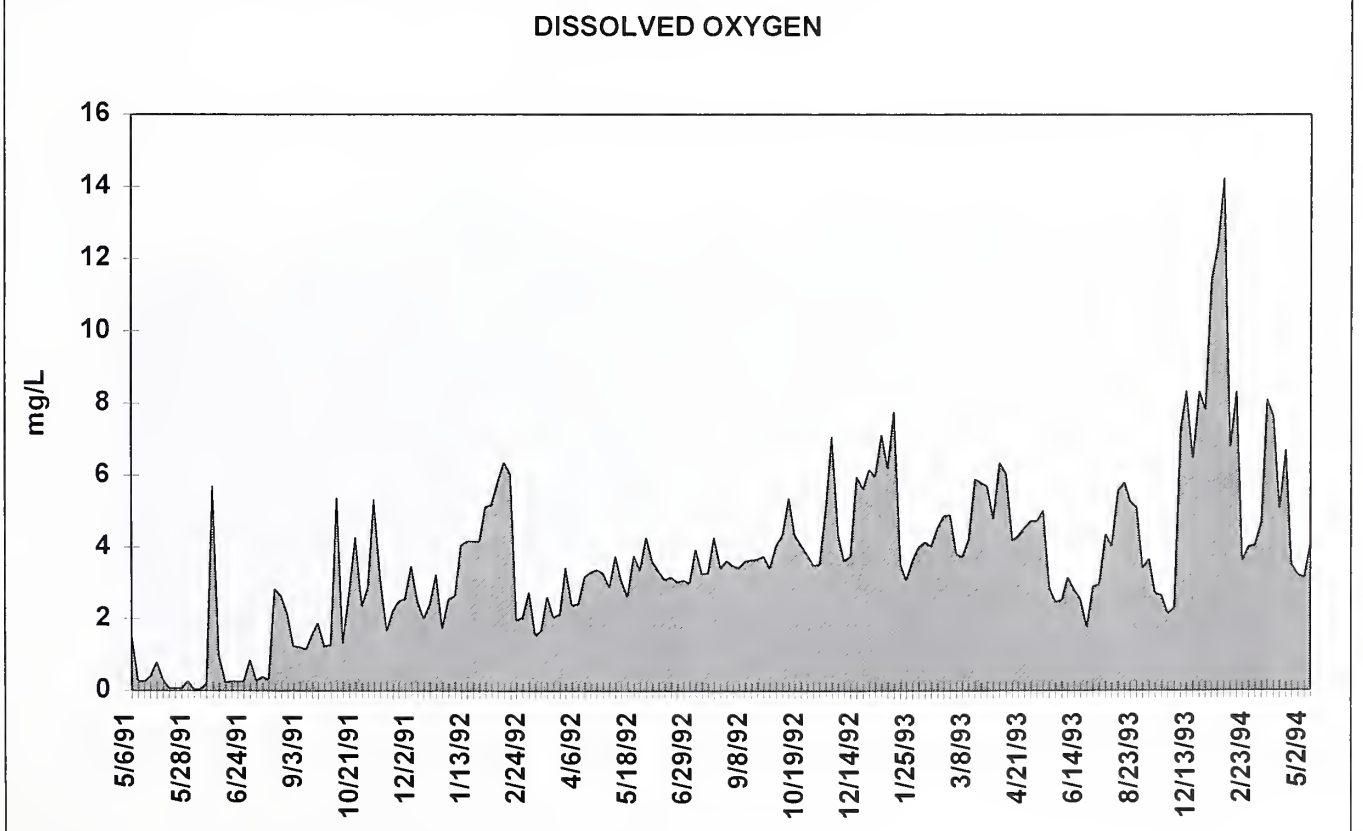

Figure 7a. Dissolved oxygen concentrations by date.

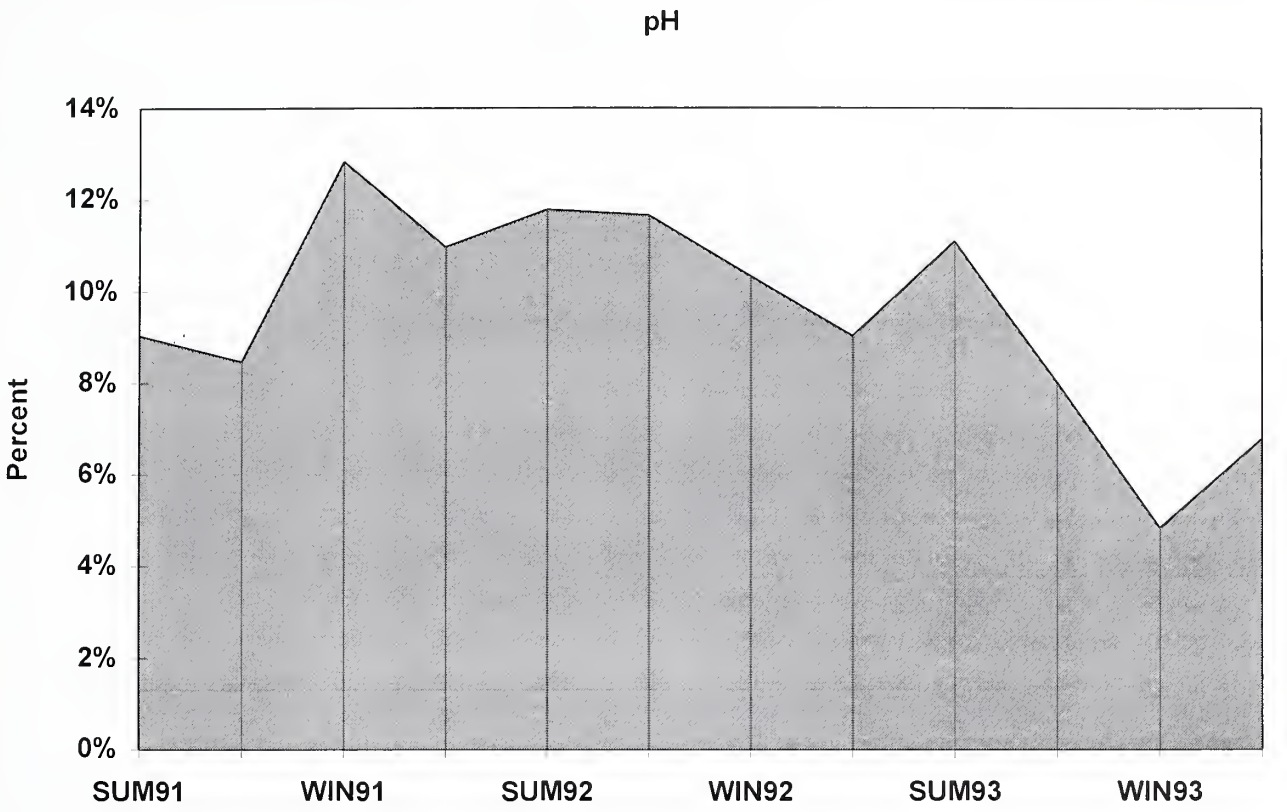

Figure 8. pH reduction in wetland by season.

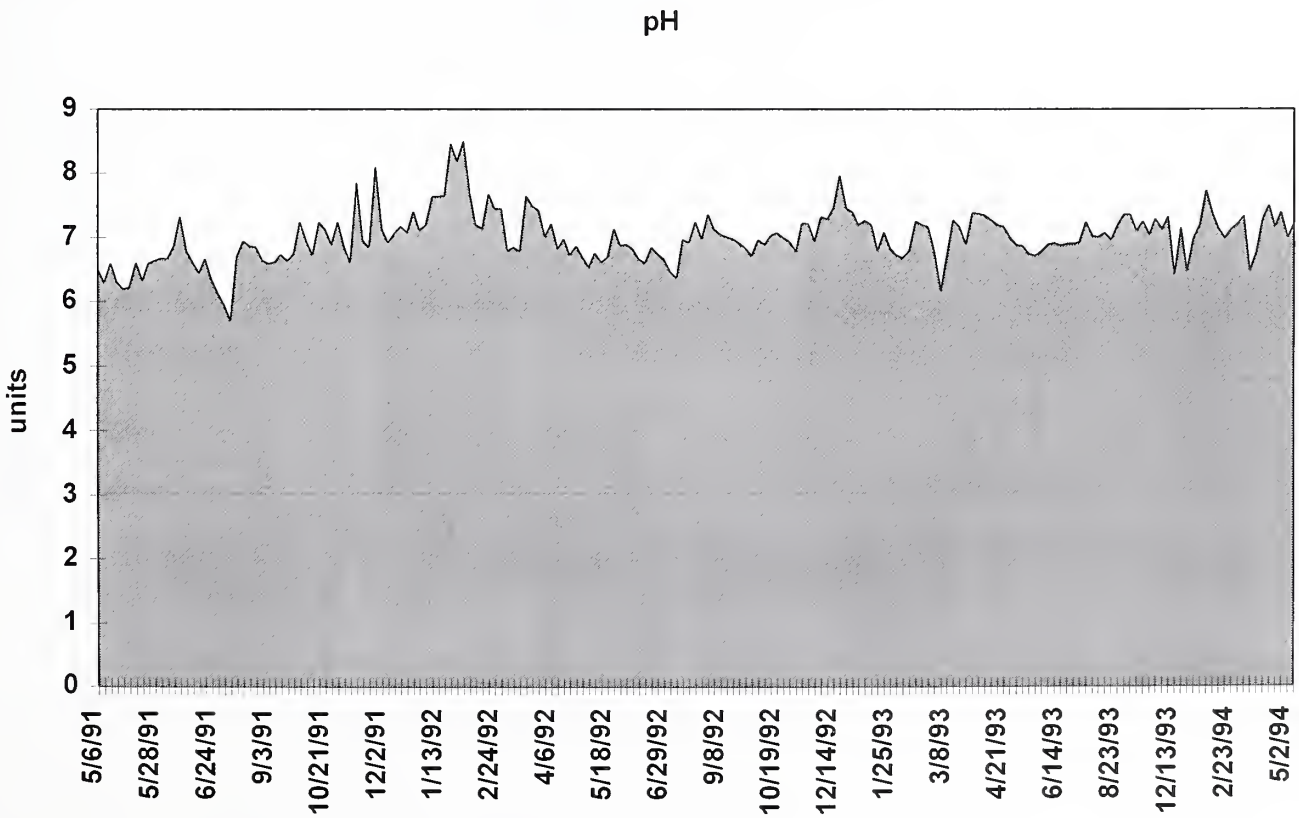

Figure 8a. Inflow pH values by date.

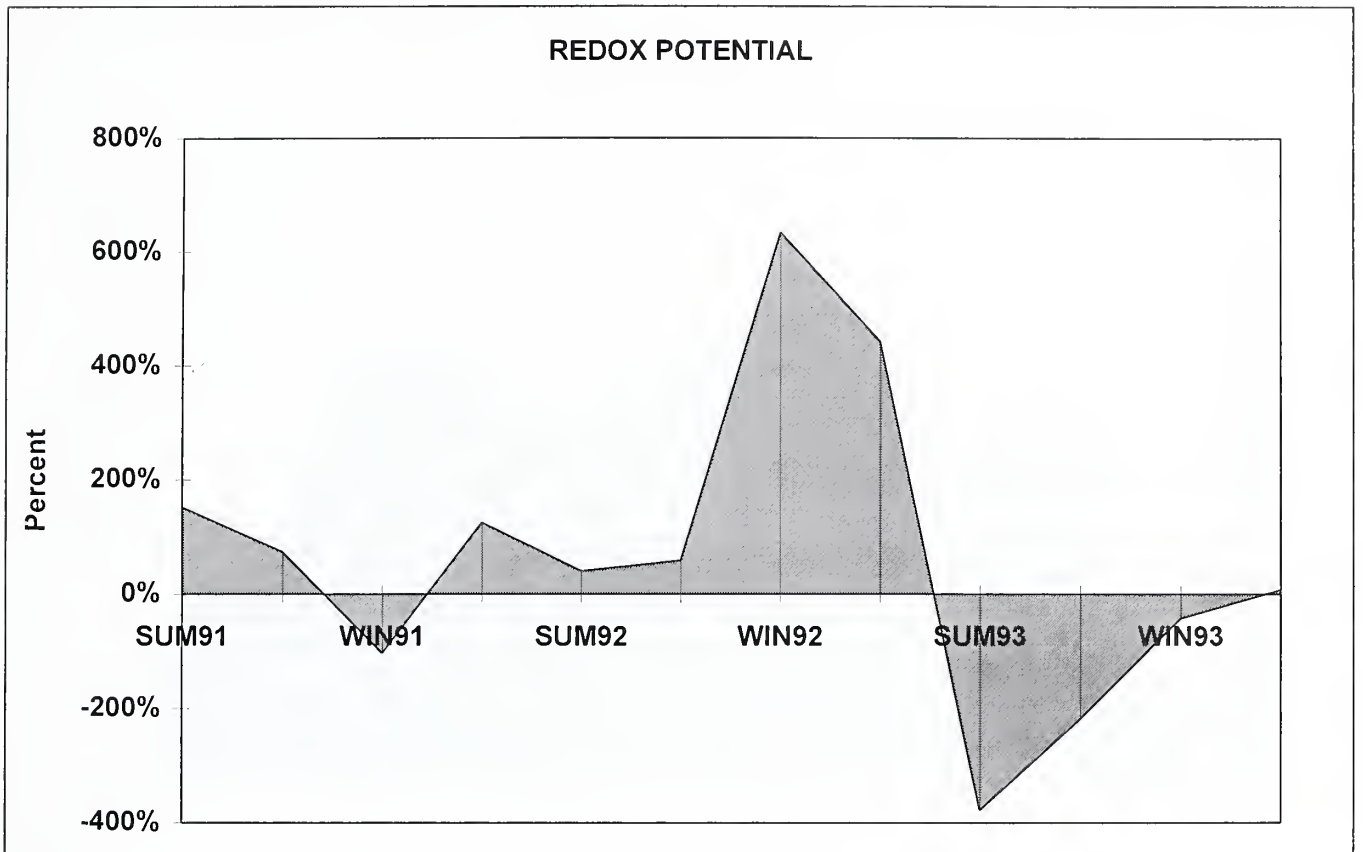

Figure 9. Redox potential reduction in wetland by season.

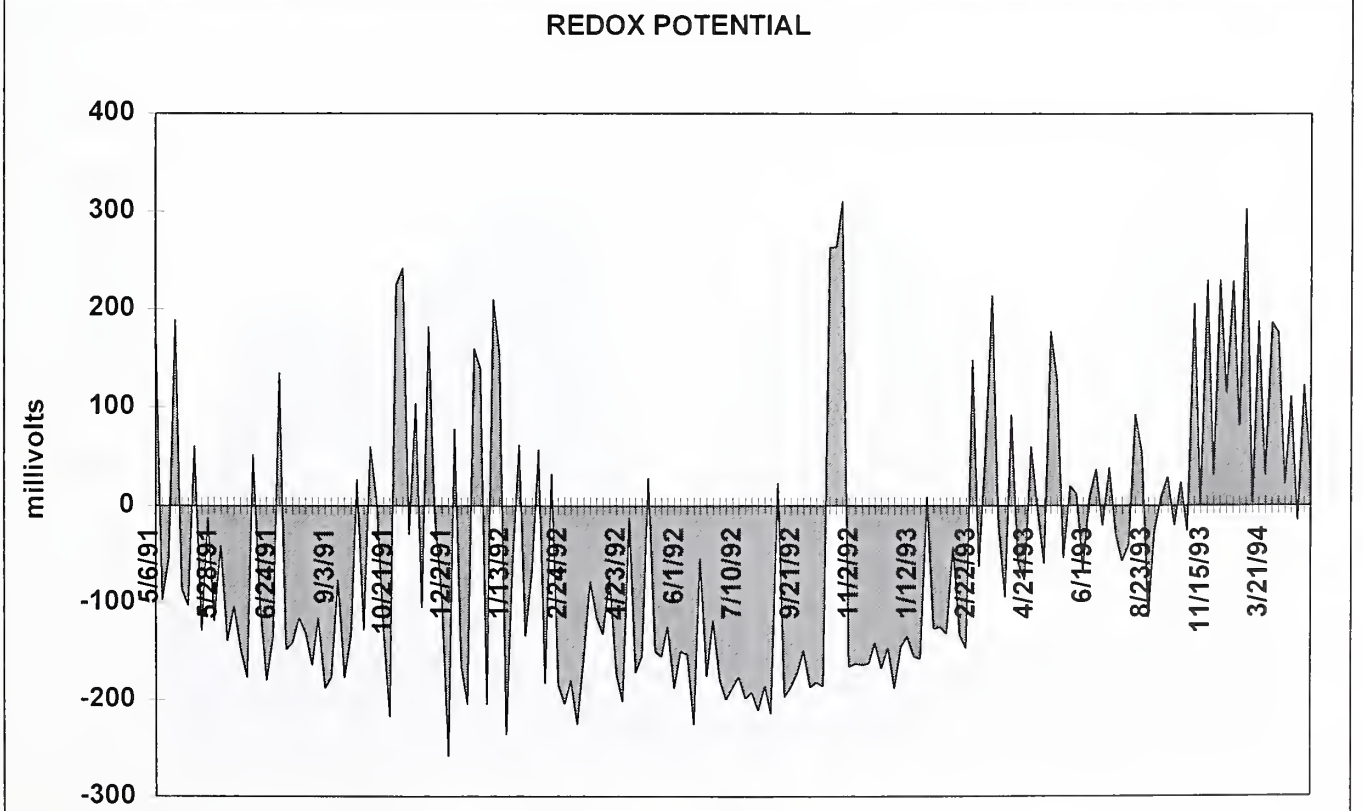

Figure 9a. Inflow redox potential values by date

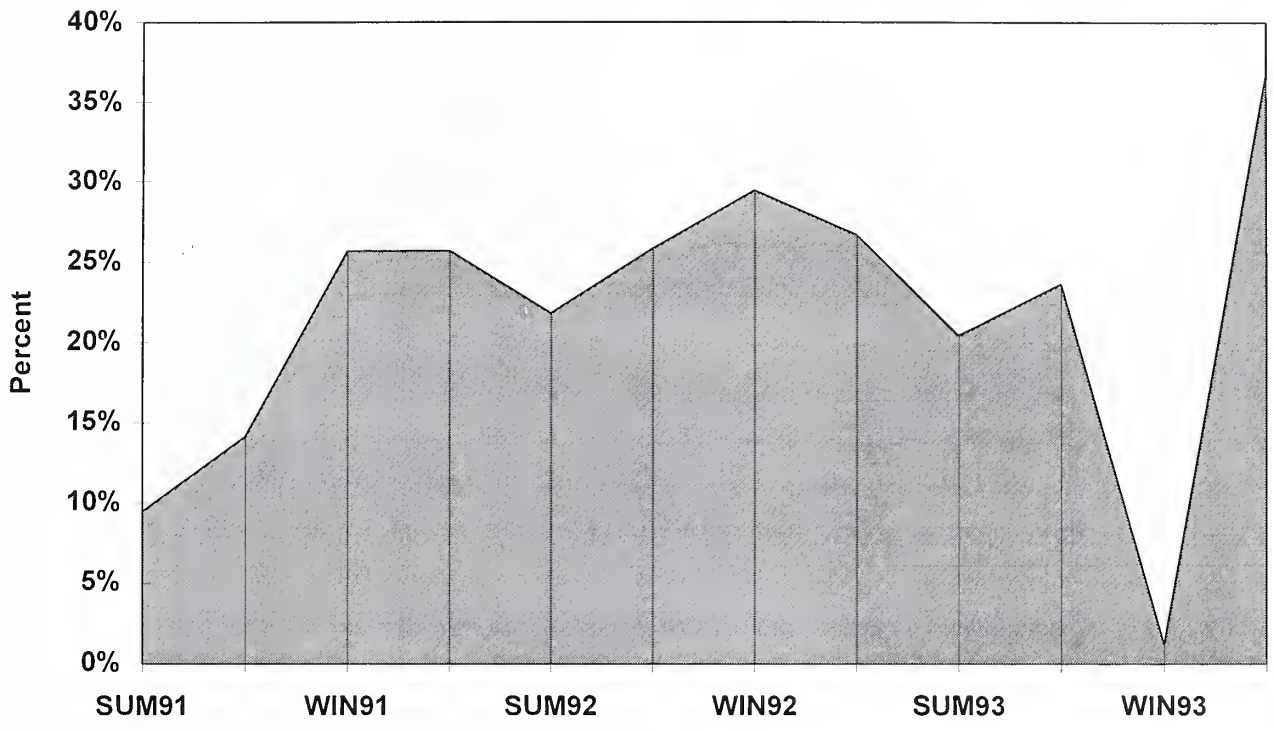

Figure 10. Dissolved solids reduction in wetland by season.

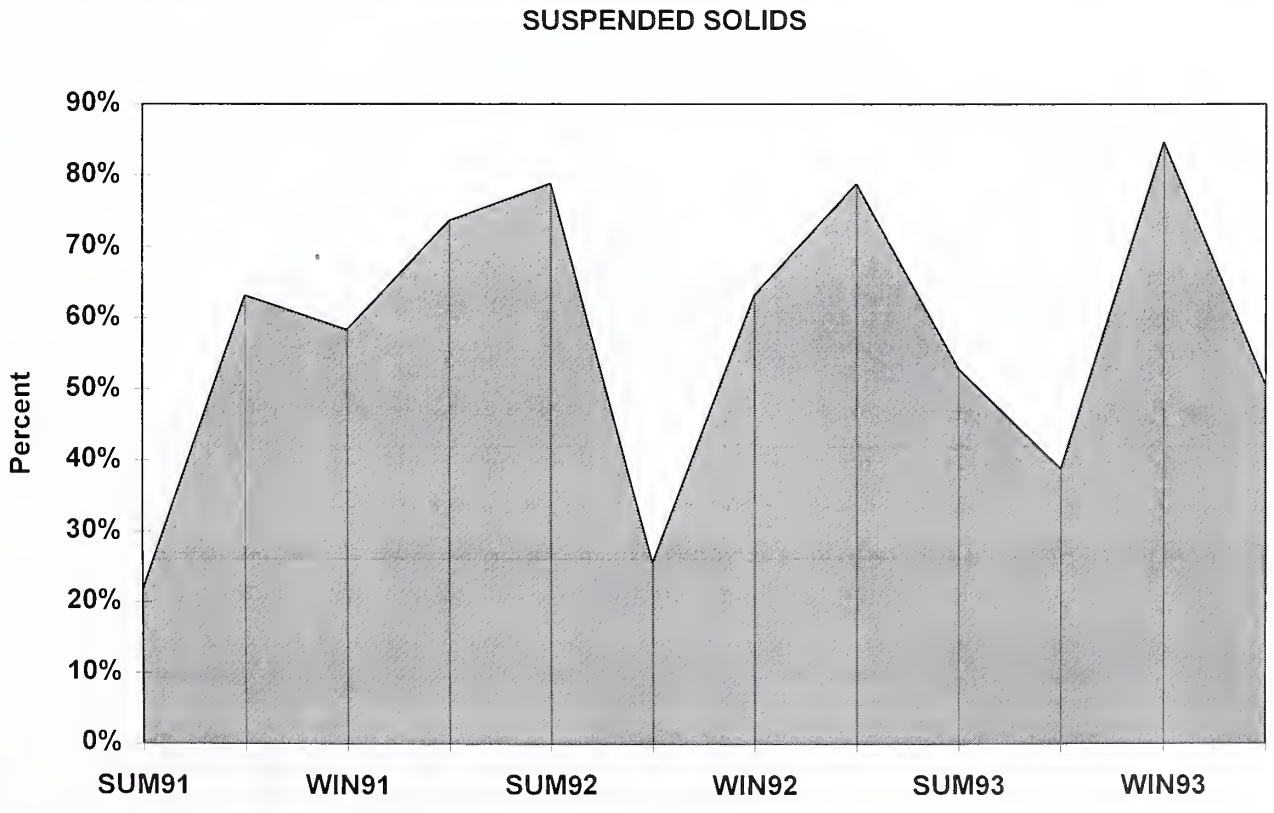

Figure 11. Suspended solids reduction in wetland by season.

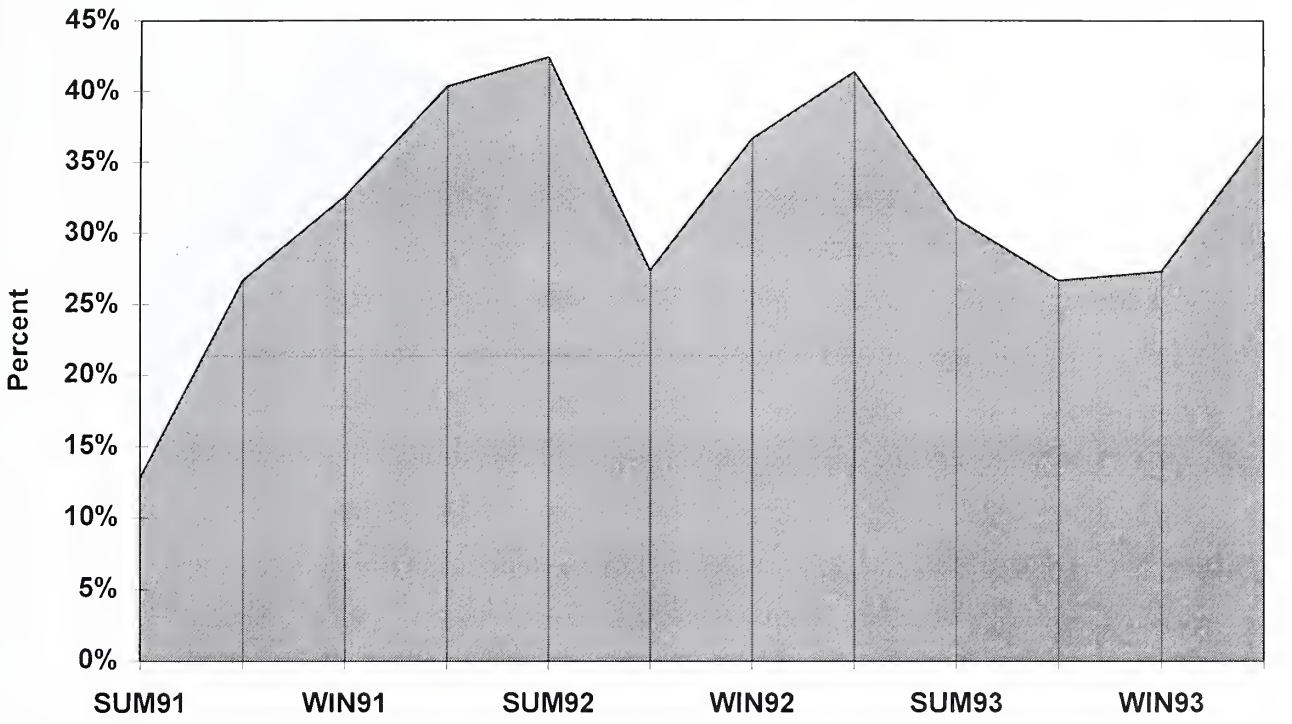

Figure 12. Total solids reduction in wetland by season.

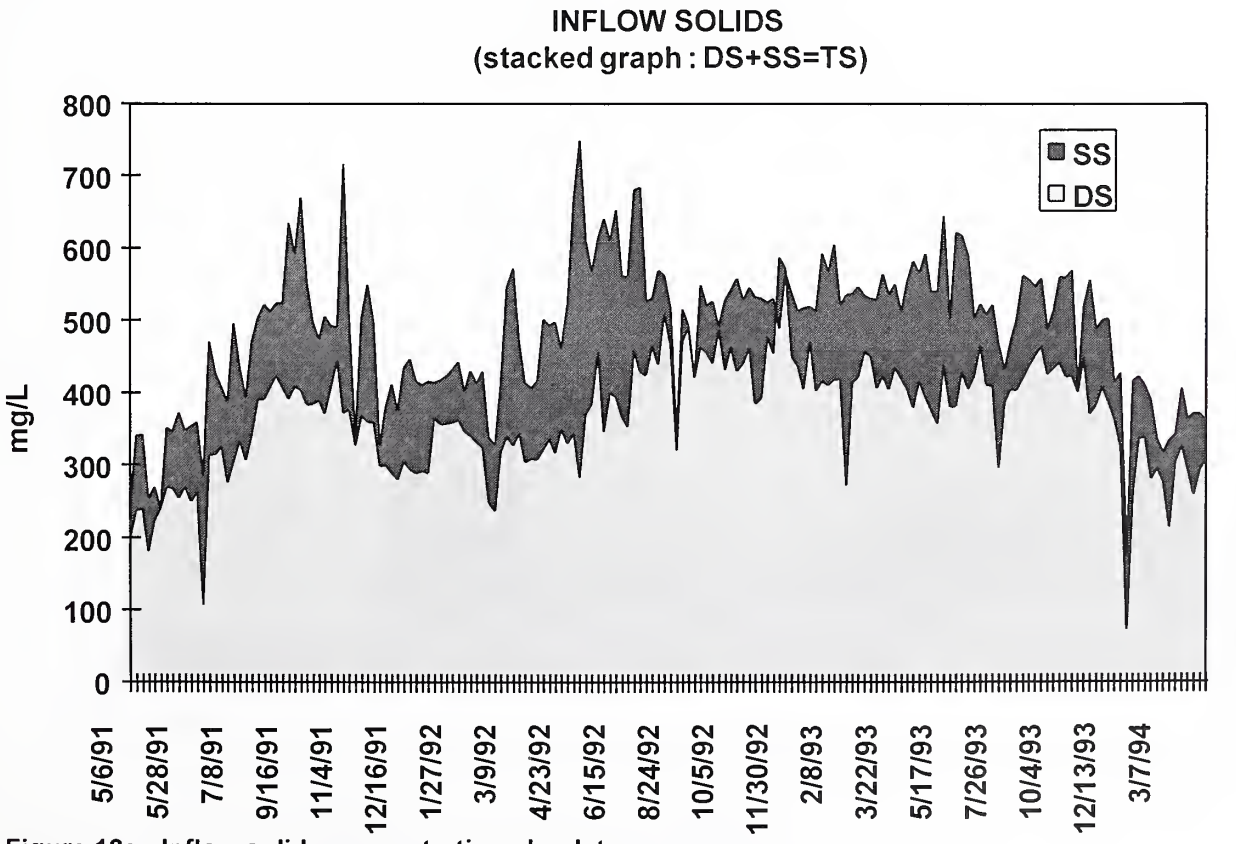

Figure 12a. Inflow solids concentrations by date.

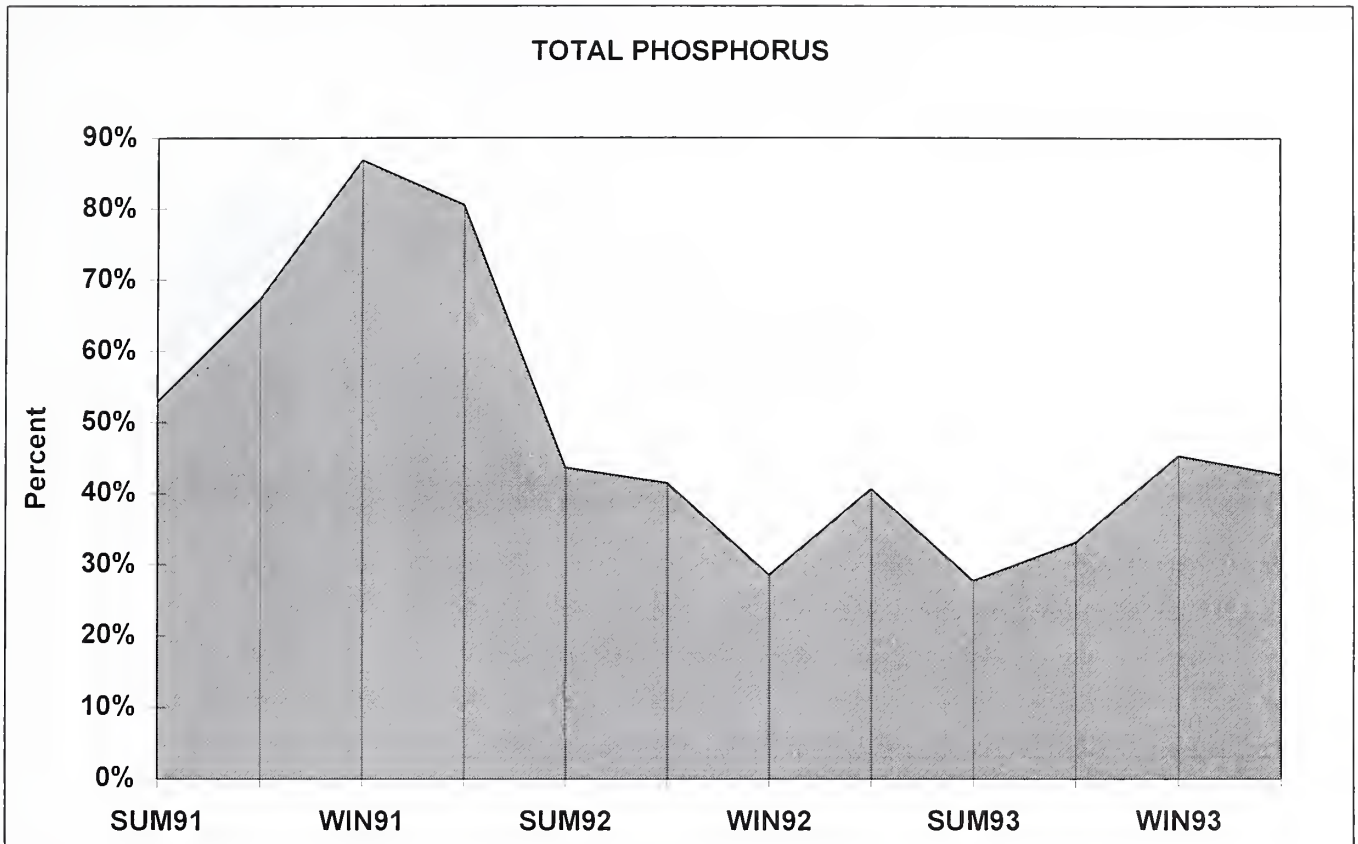

Figure 13. Total phosphorus reduction in wetland by season.

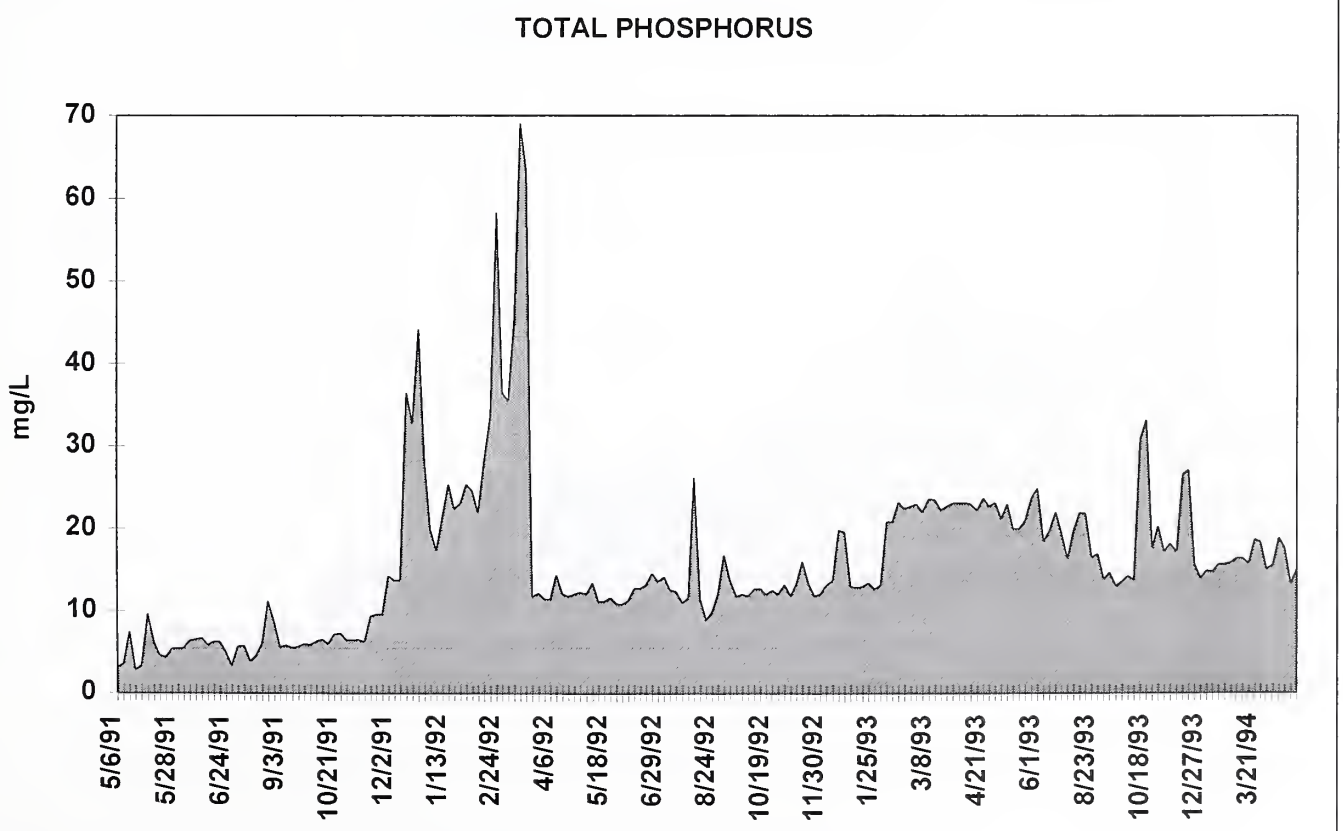

Figure 13a. Inflow total phosphorus concentrations by date.

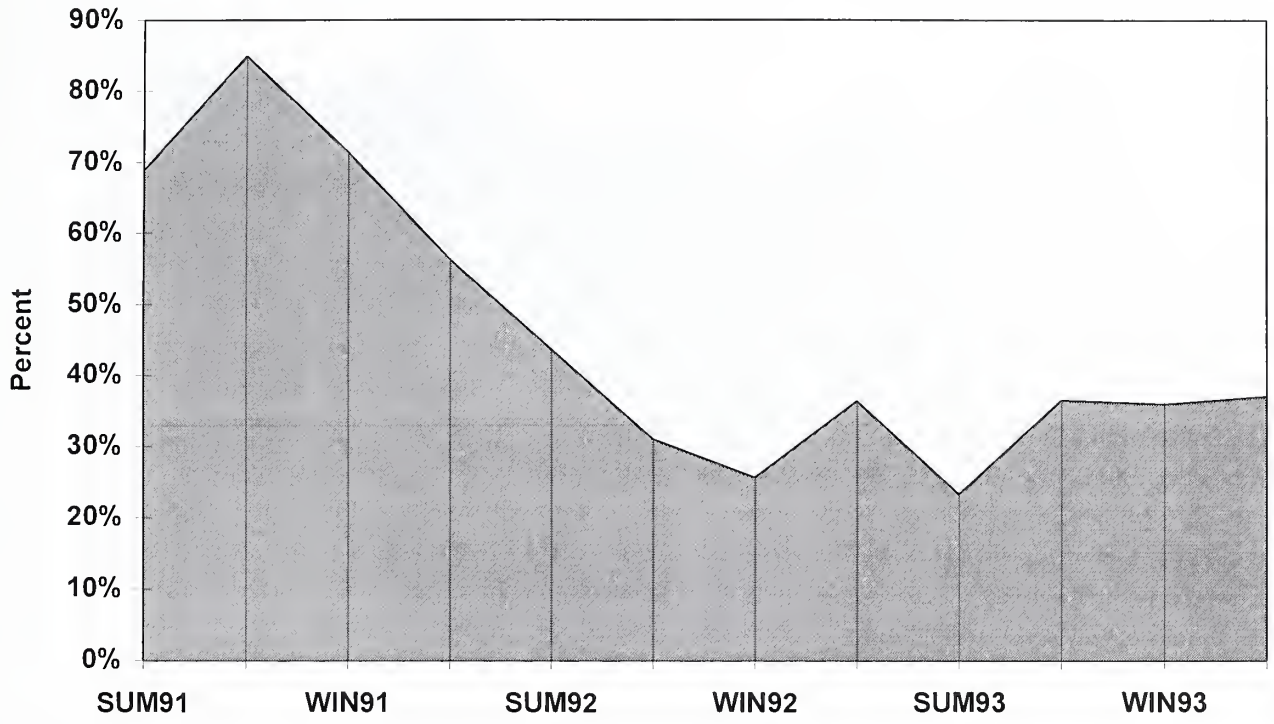

Figure 14. Filterable ortho-phosphorus reduction in wetland by season.

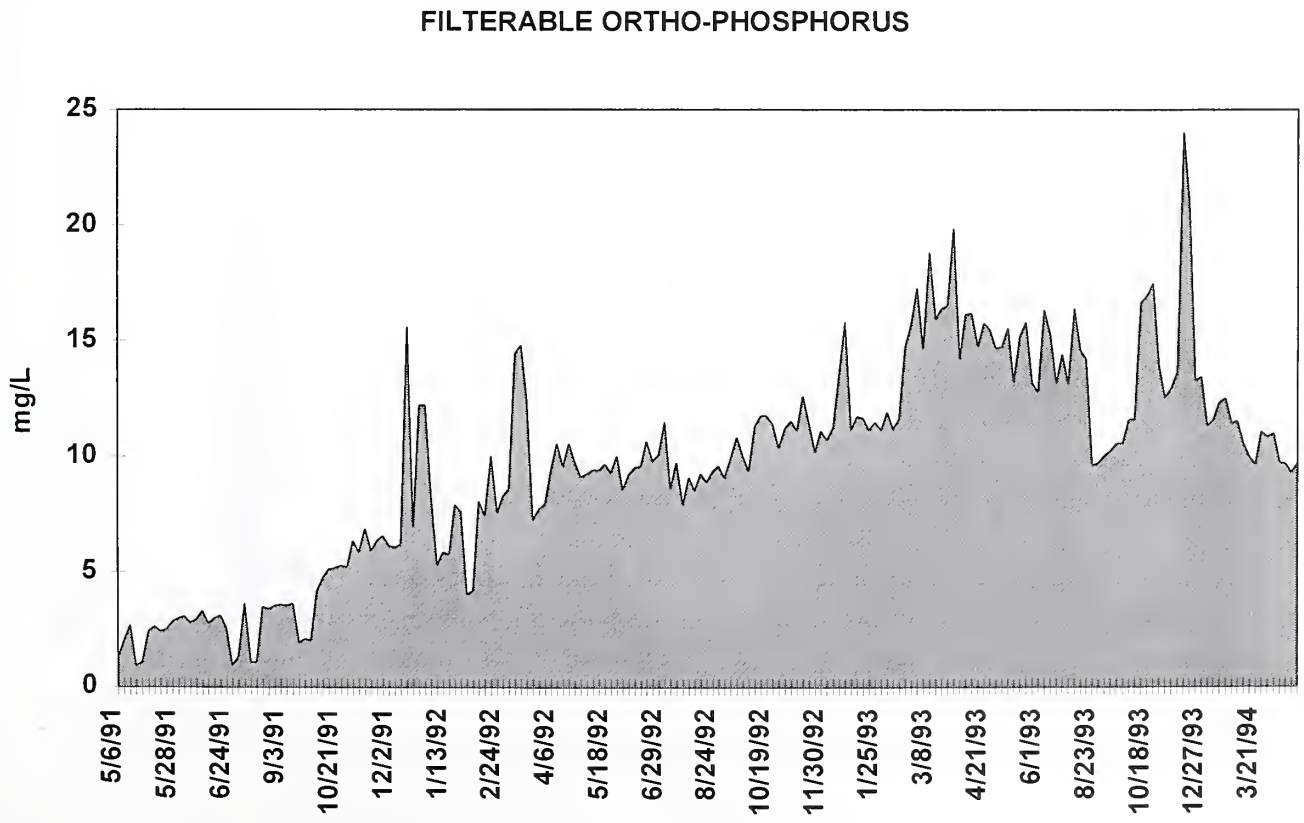

Figure 14a. Inflow filterable ortho-phosphorus concentrations by date.

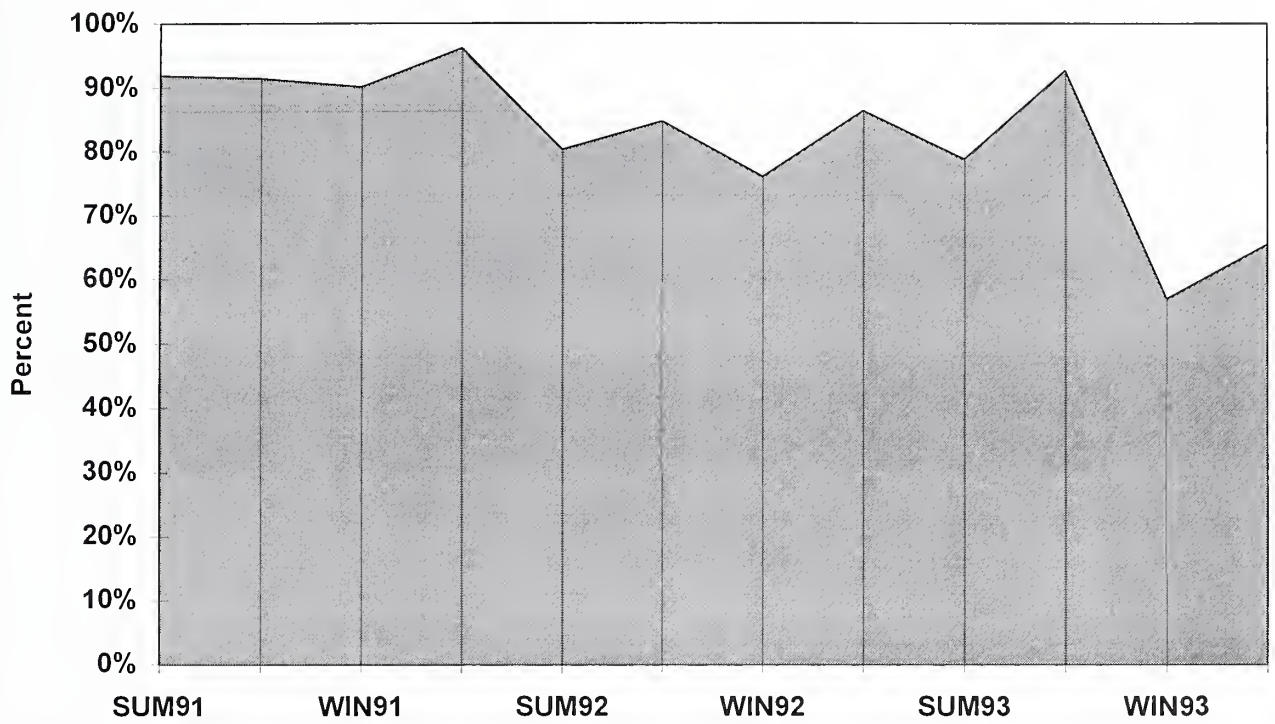

Figure 15. Ammonia nitrogen reduction in wetland by season.

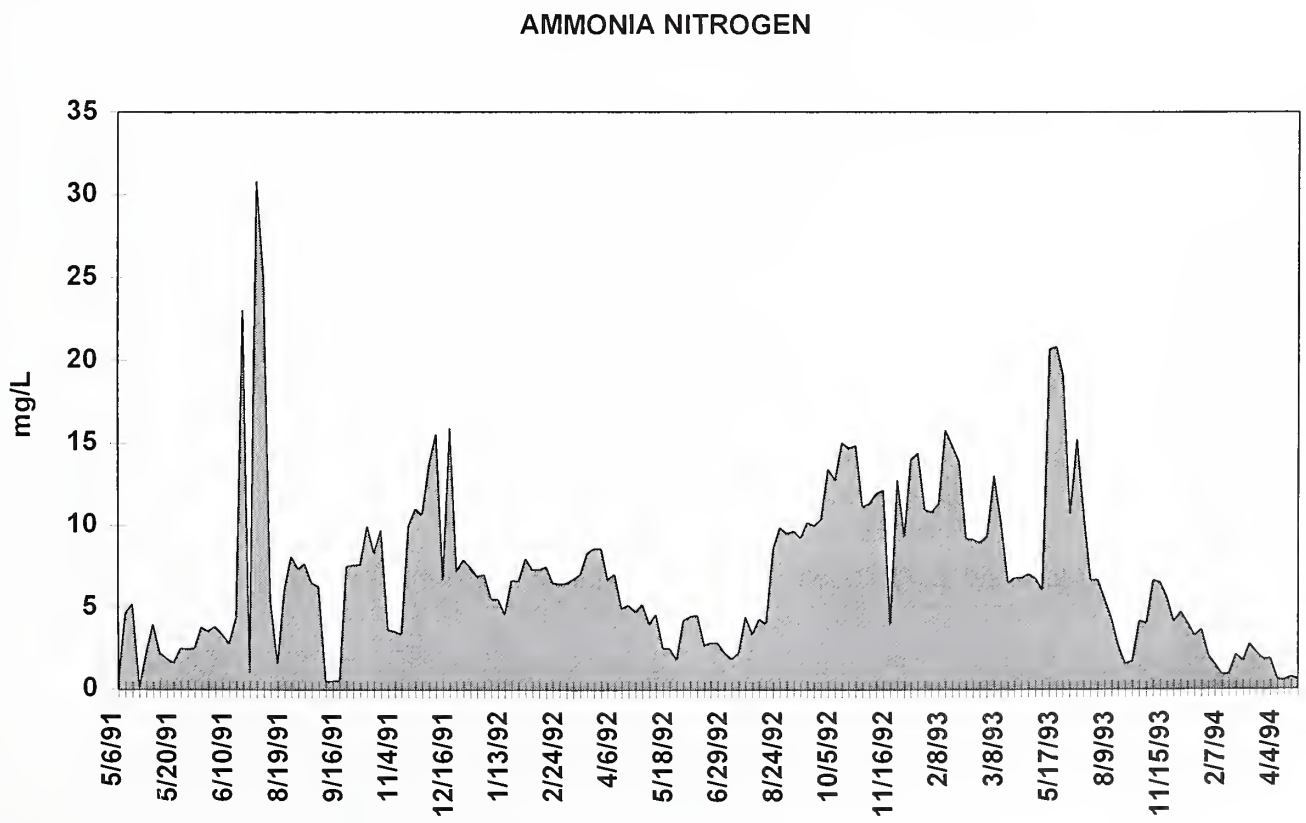

Figure 15a. Inflow ammonia nitrogen concentrations by date.

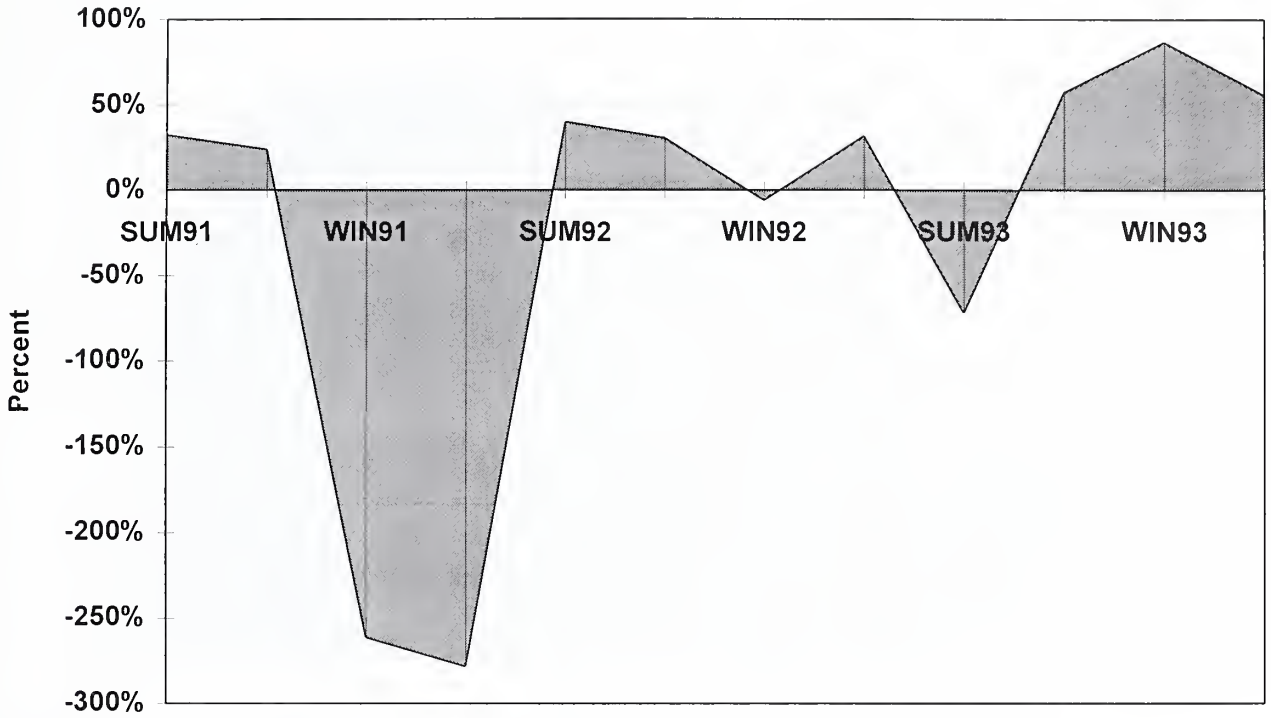

Figure 16. Nitrate nitrogen reduction in wetland by season.

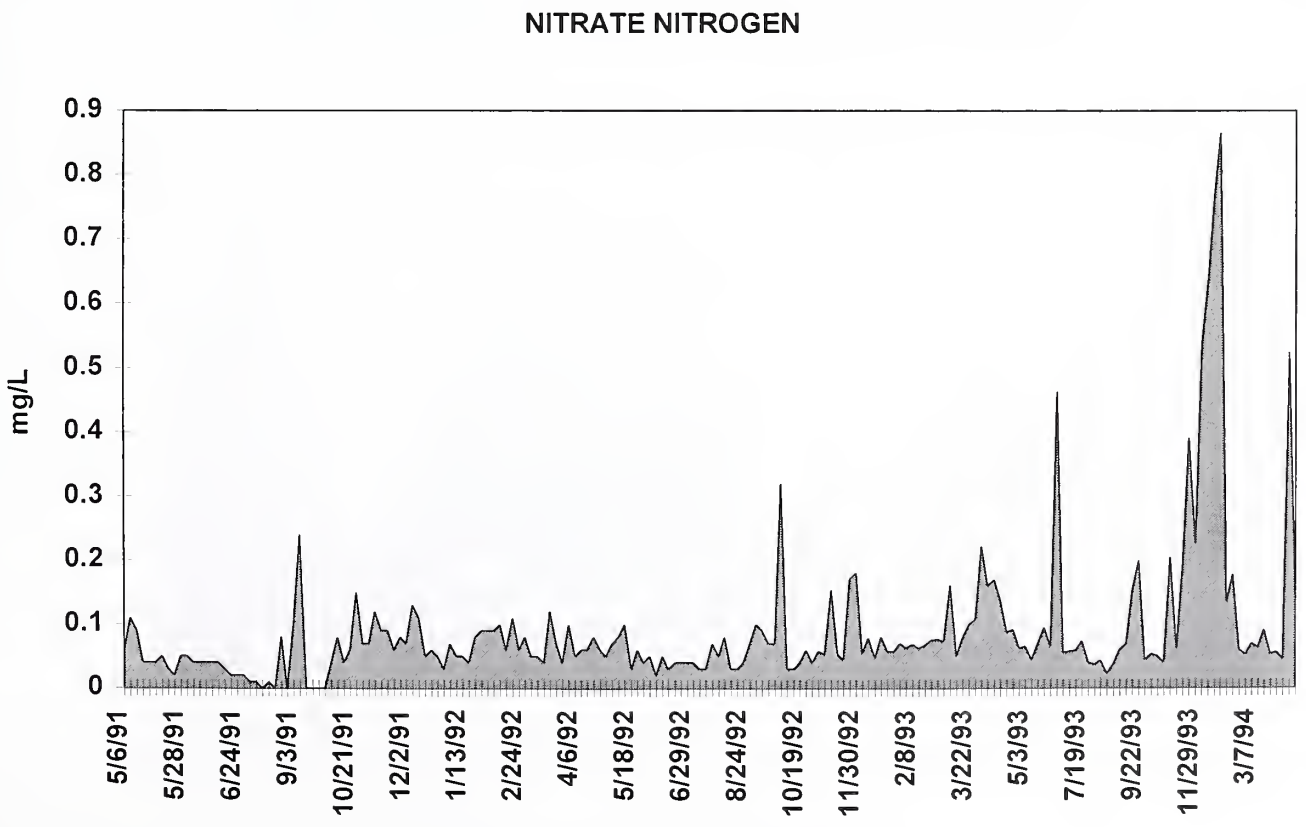

Figure 16a. Nitrate nitrogen concentrations by date.

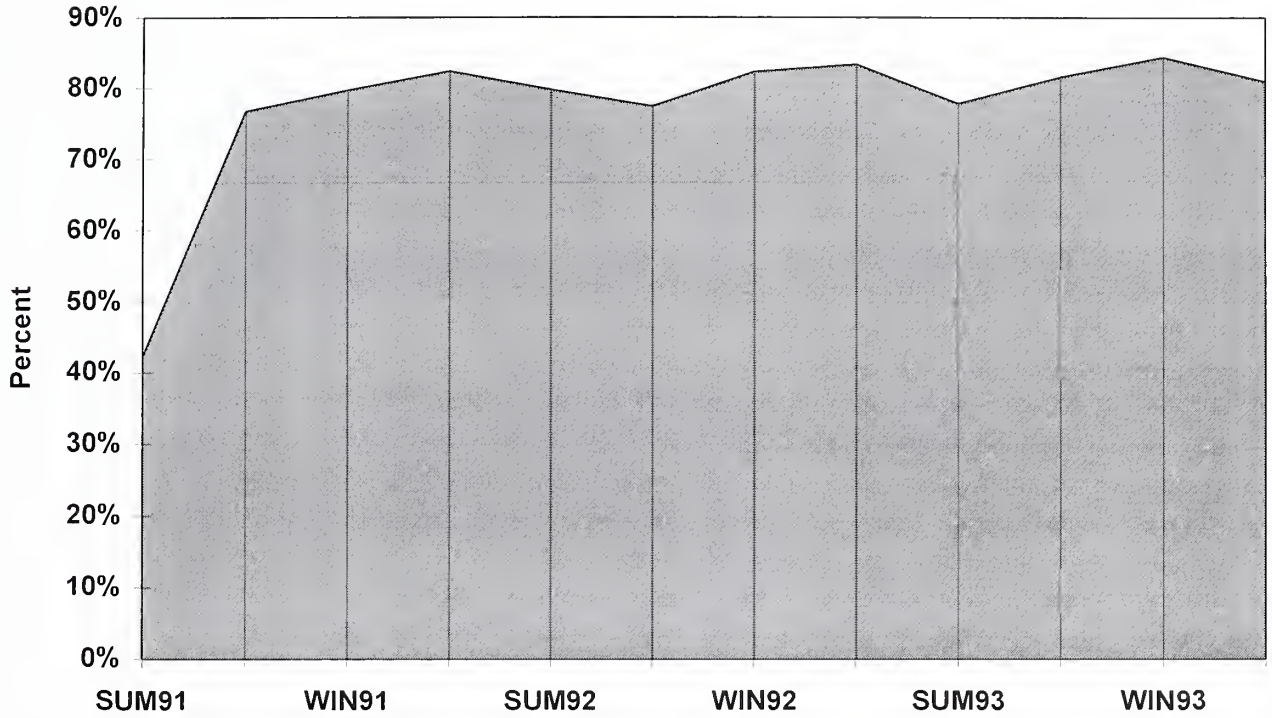

Figure 17. 5-Day carbonaceous biochemcial oxygen reduction in wetland by season.

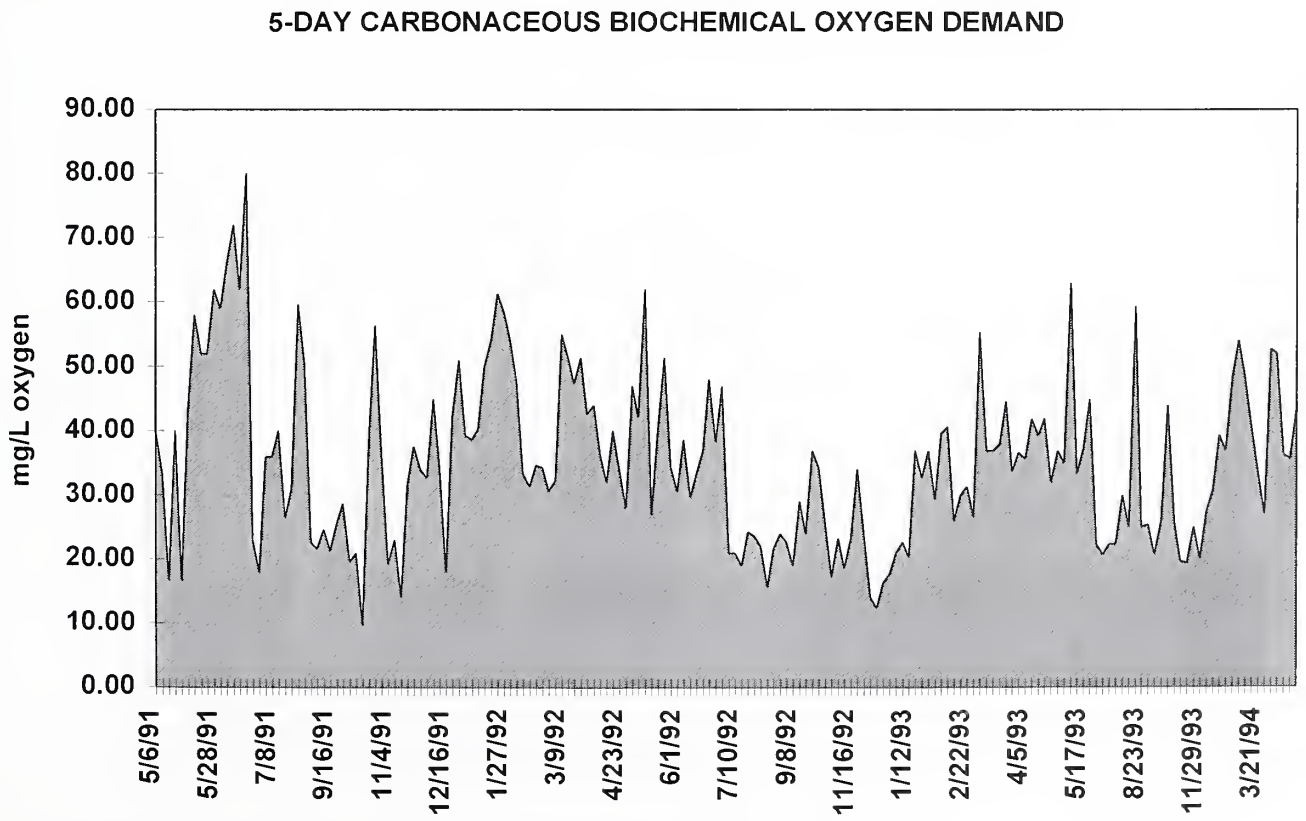

Figure 17a. Inflow 5-day biochemical oxygen demand values by date.

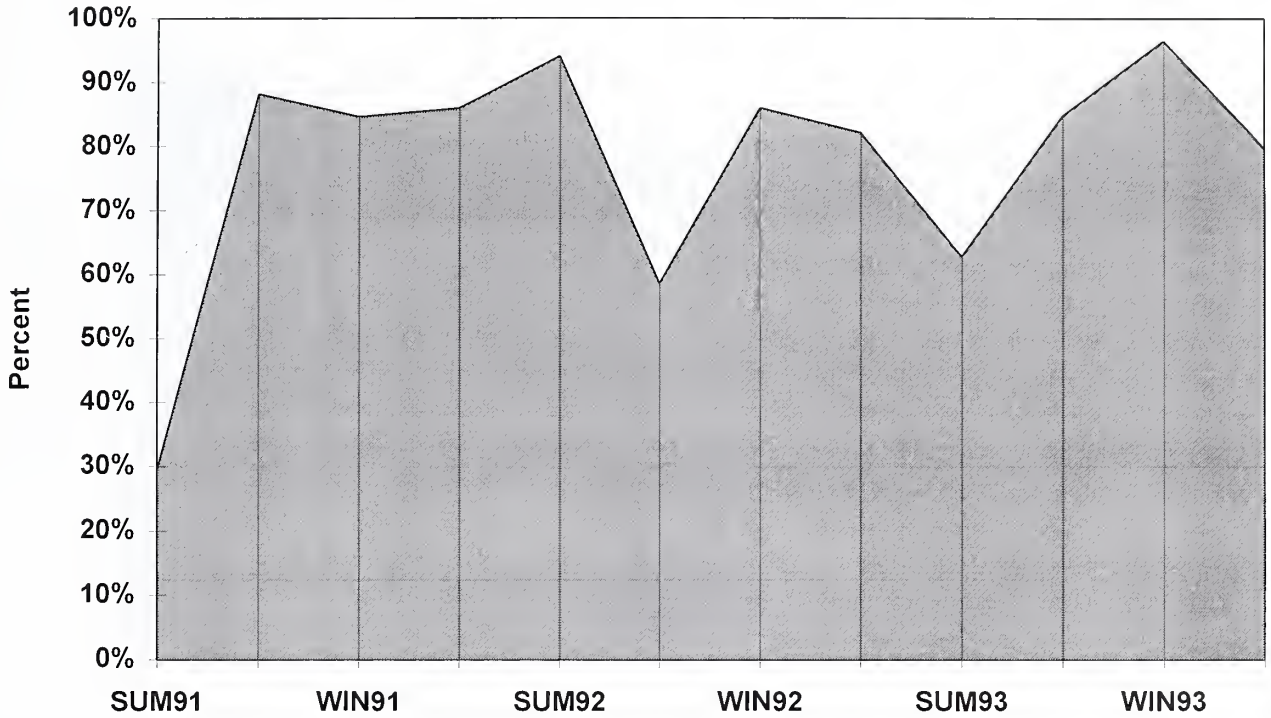

Figure 18. Chlorophyll reduction in wetland by season.

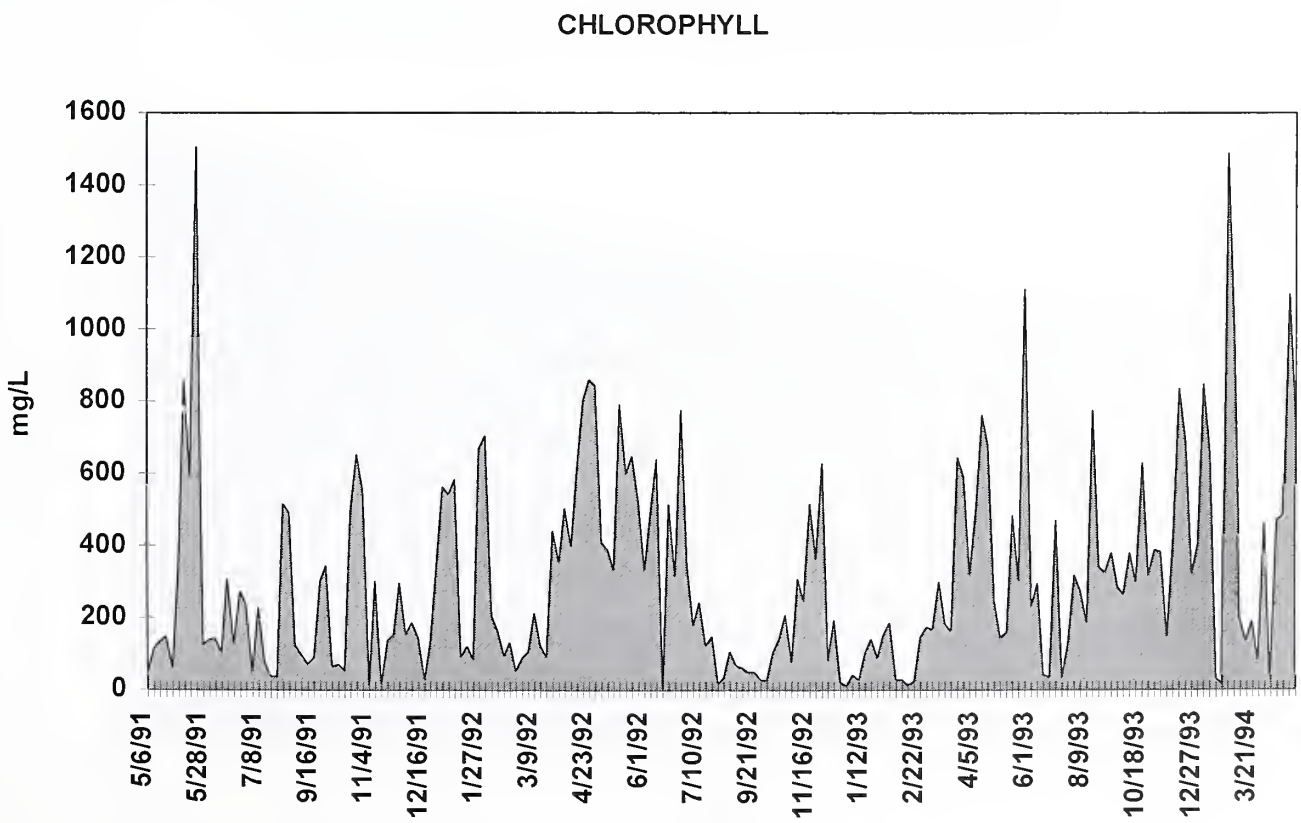

Figure 18a. Inflow chlorophyll concentrations by date.

FIGURE 19. CELL 2 MEAN VALUES FOR TEMPERATURE

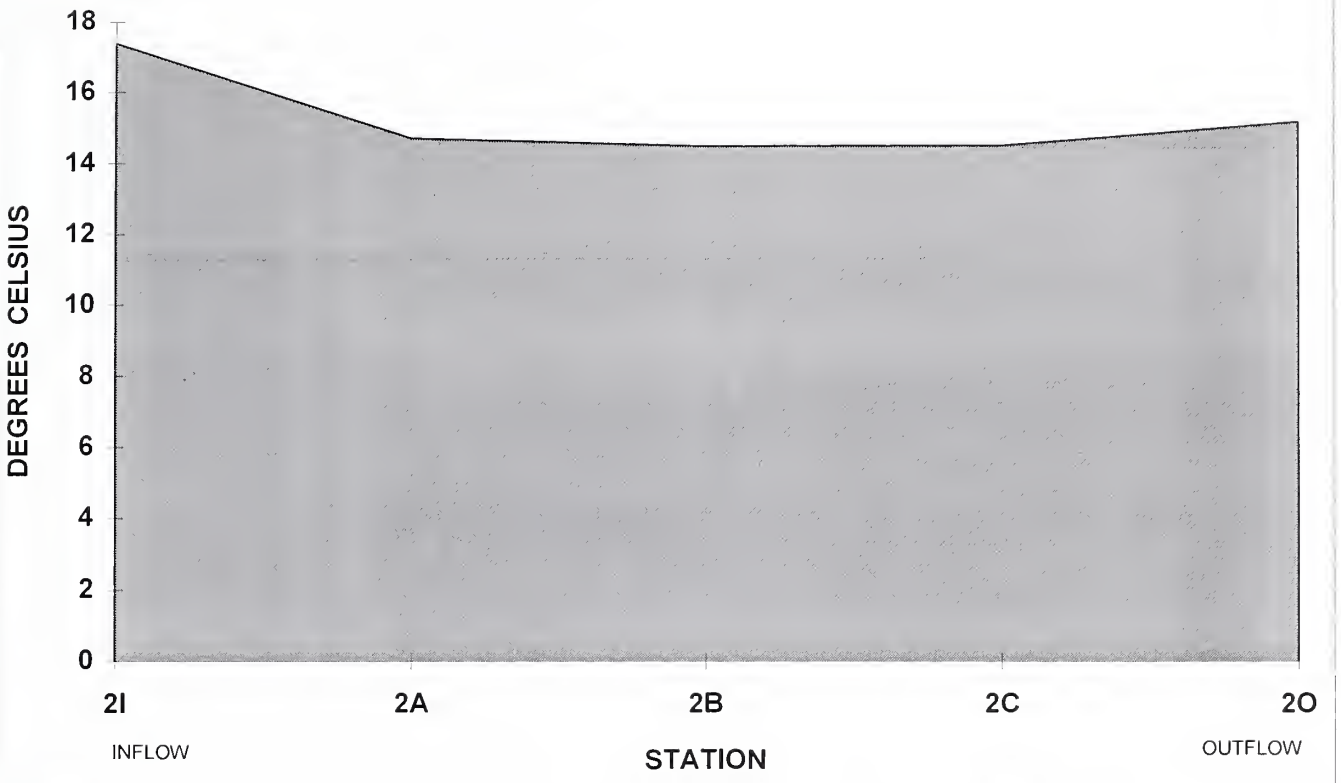

FIGURE 20. CELL 2 MEAN VALUES FOR CONDUCTIVITY

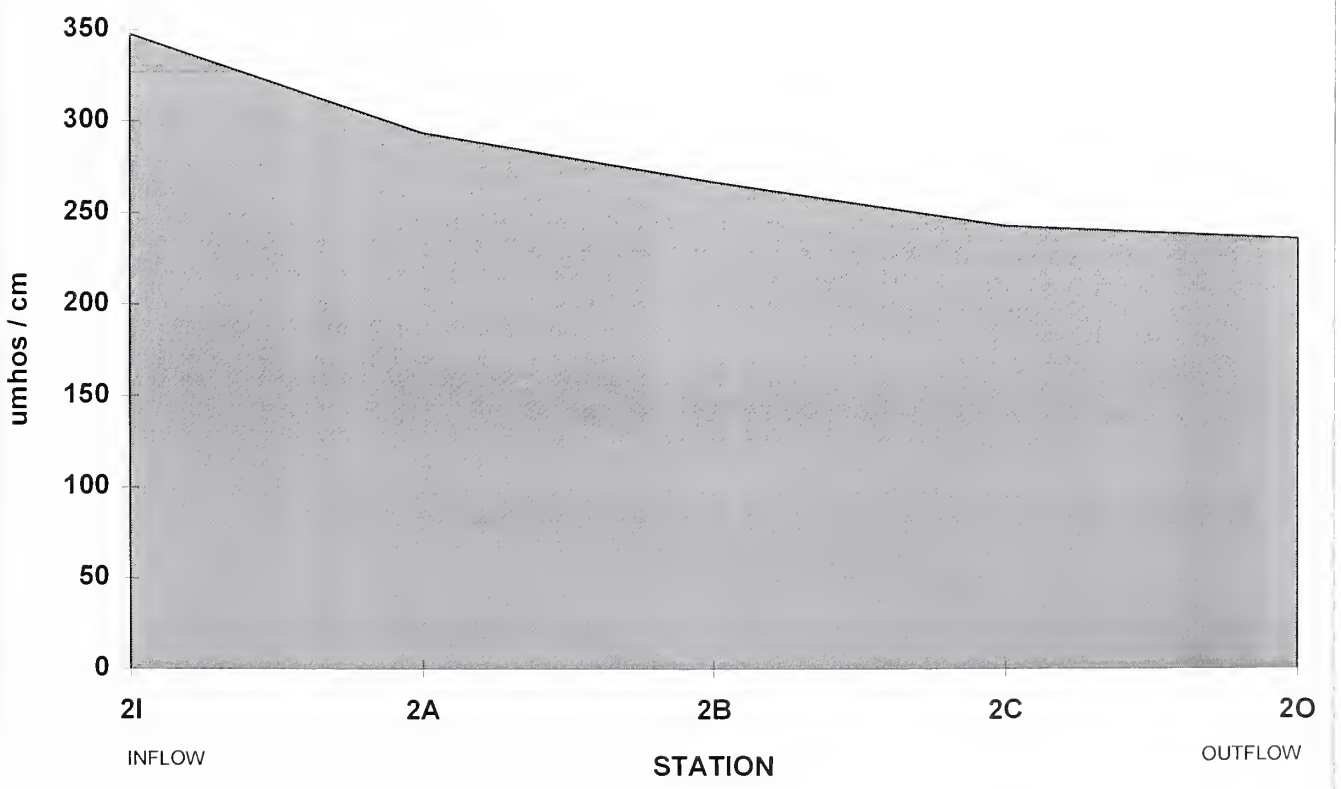

FIGURE 21. CELL 2 MEAN CONCENTRATIONS FOR DISSOLVED OXYGEN

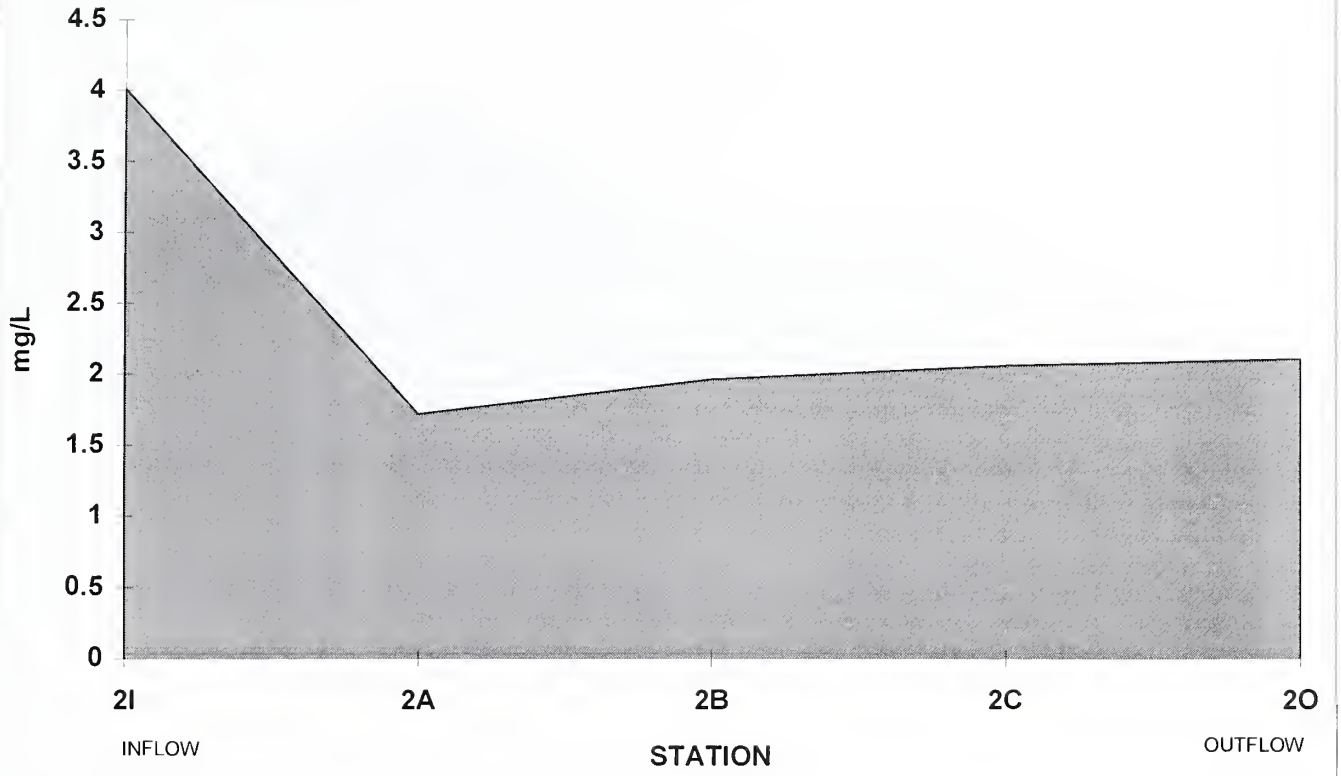

FIGURE 22. CELL 2 MEAN VALUES FOR pH

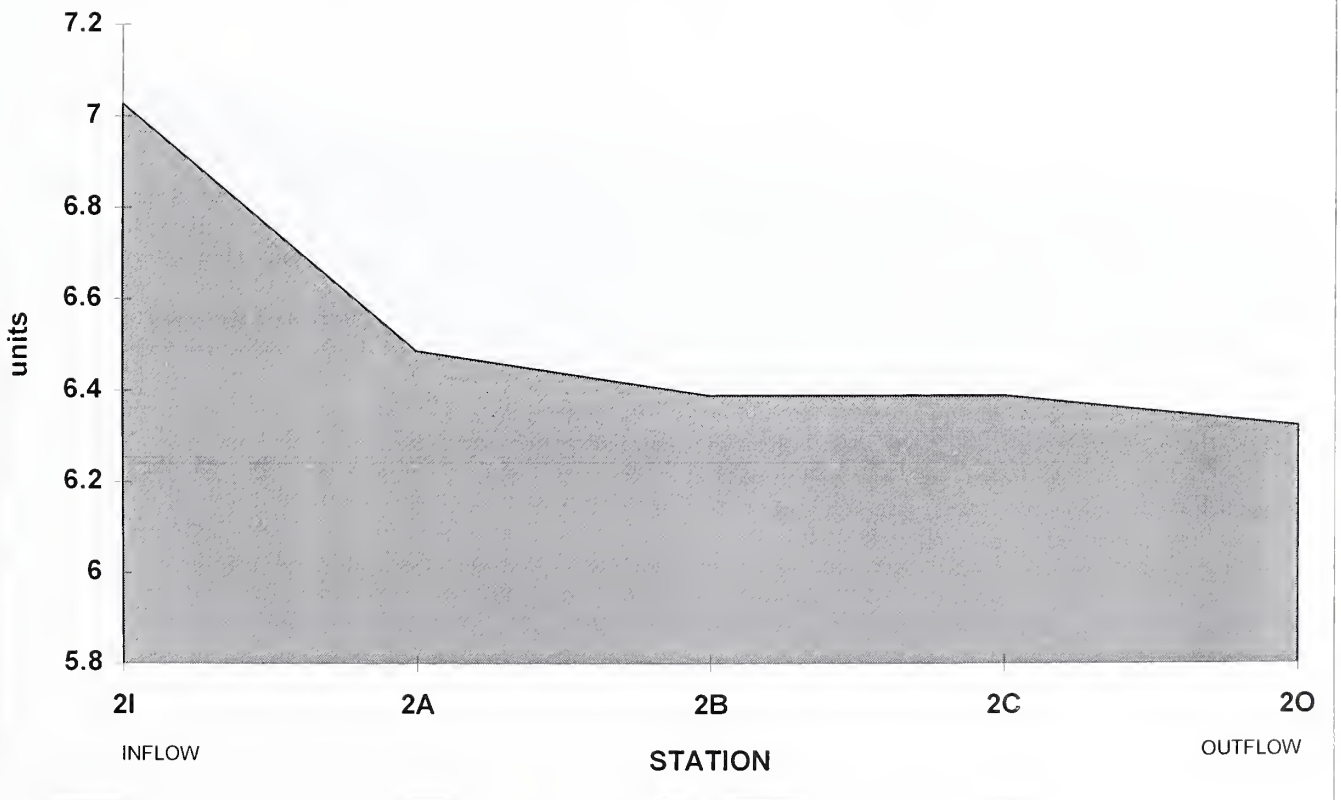

FIGURE 23. CELL 2 MEAN CONCENTRATIONS FOR TOTAL SOLIDS

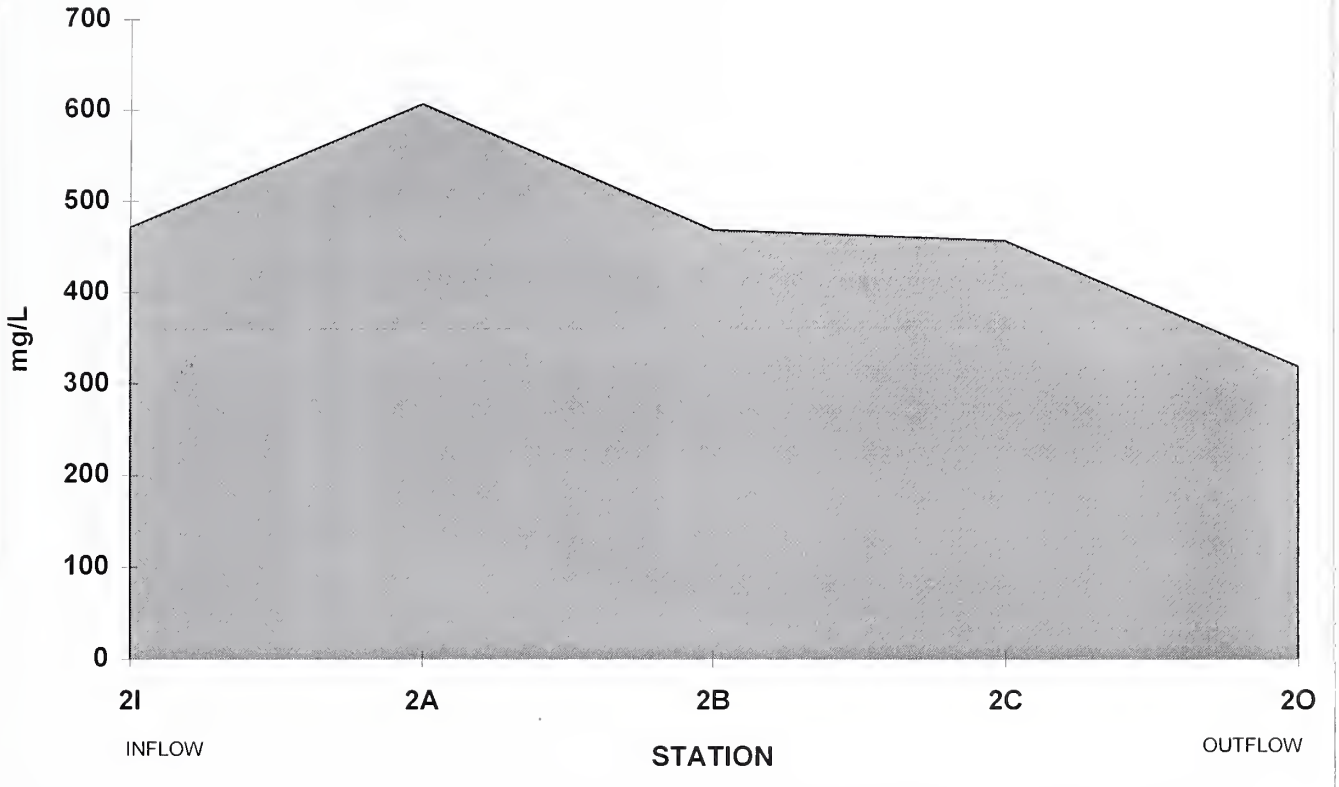

FIGURE 24. CELL 2 MEAN CONCENTRATIONS FOR DISSOLVED SOLIDS

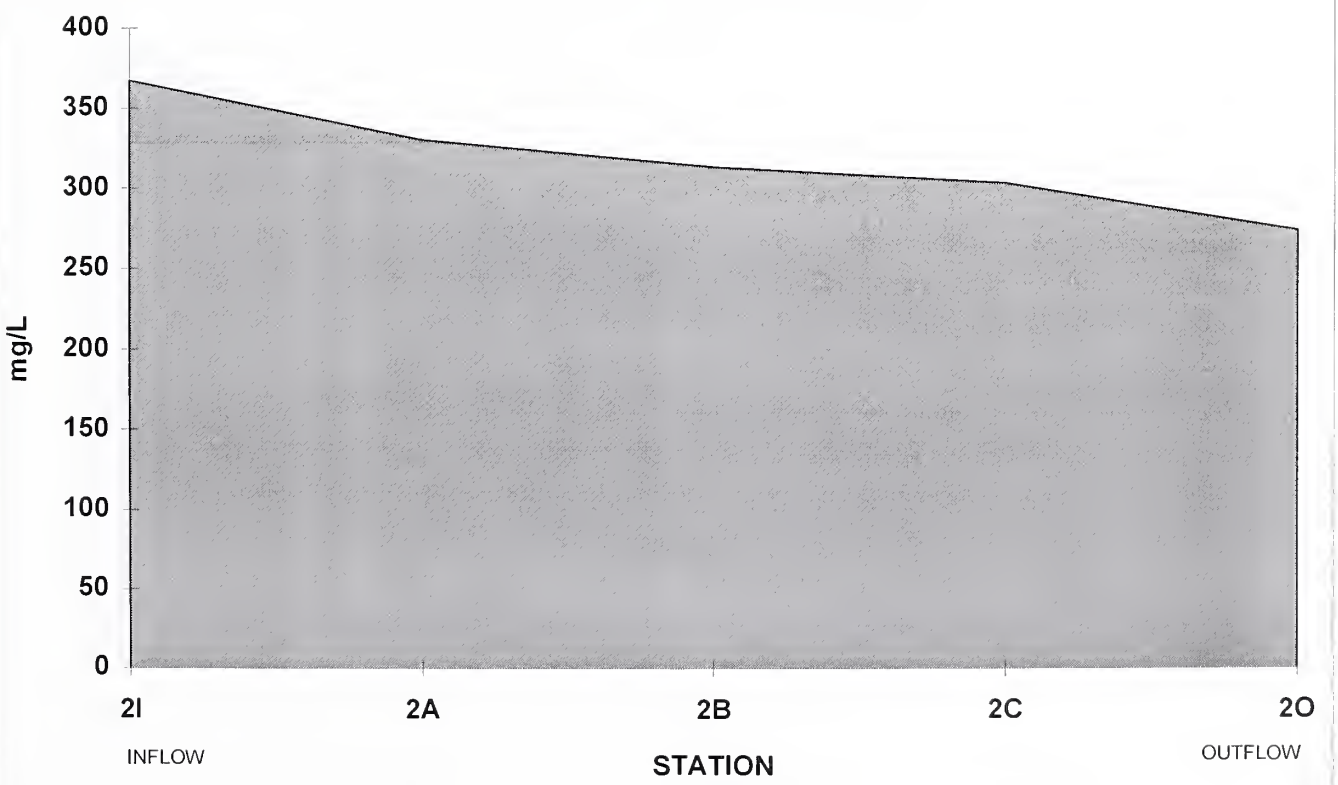

FIGURE 25. CELL 2 MEAN CONCENTRATIONS FOR SUSPENDED SOLIDS

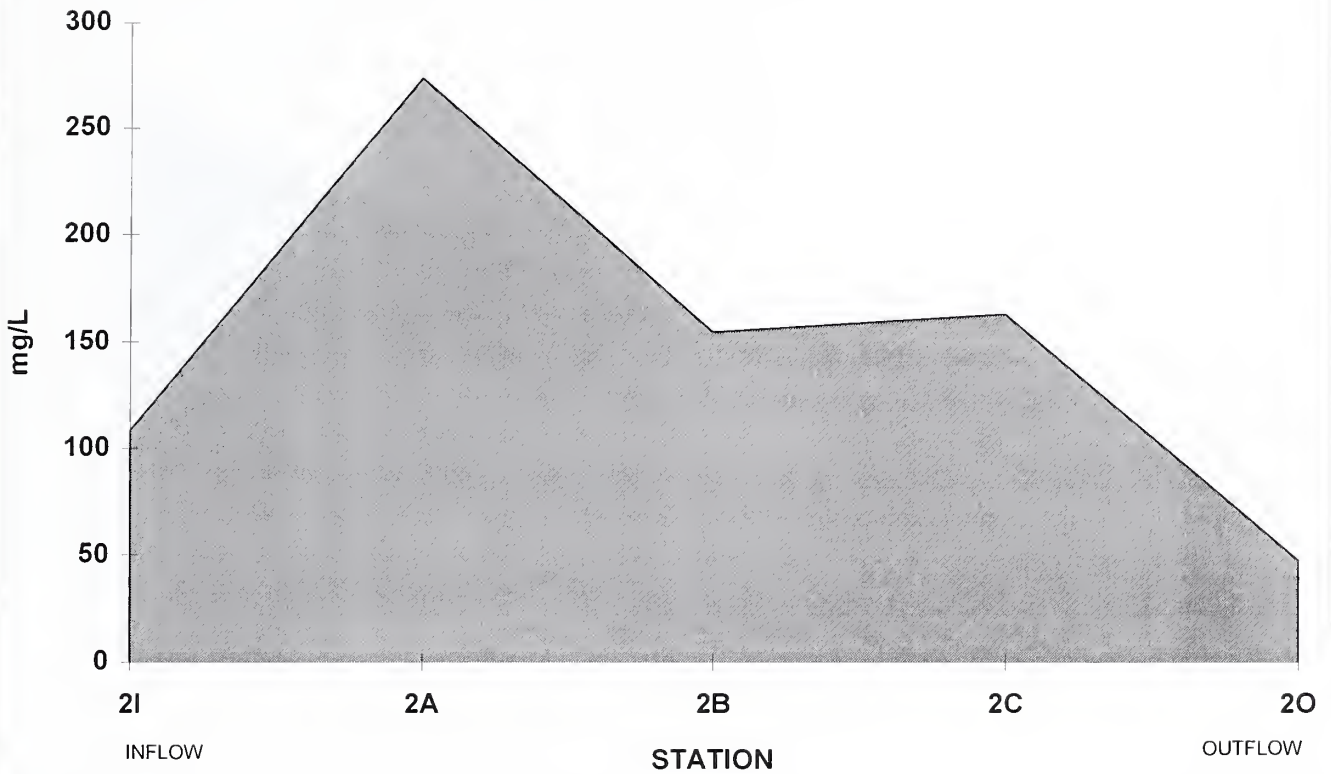

FIGURE 26. CELL 2 MEAN CONCENTRATIONS FOR FILTERABLE ORTHO-PHOSPHORUS

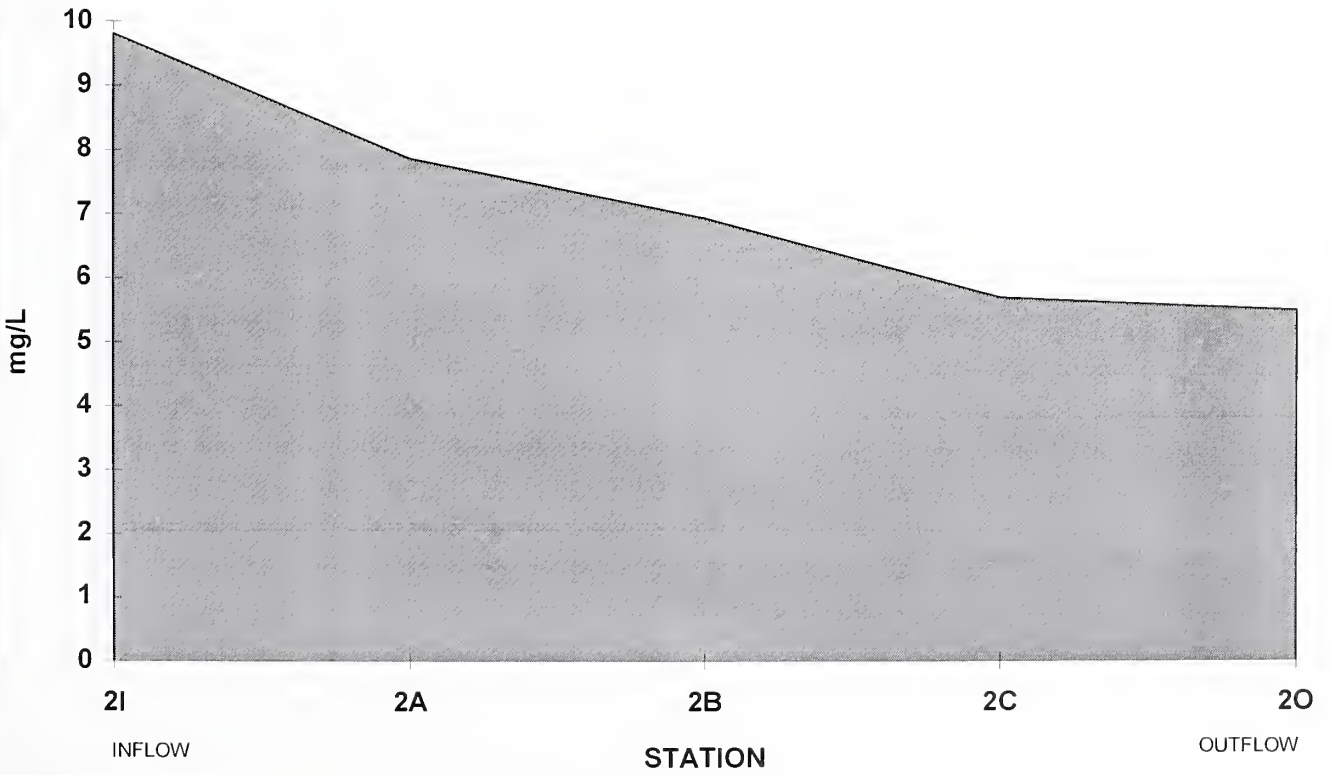

FIGURE 27. CELL 2 MEAN CONCENTRATIONS FOR TOTAL PHOSPHORUS

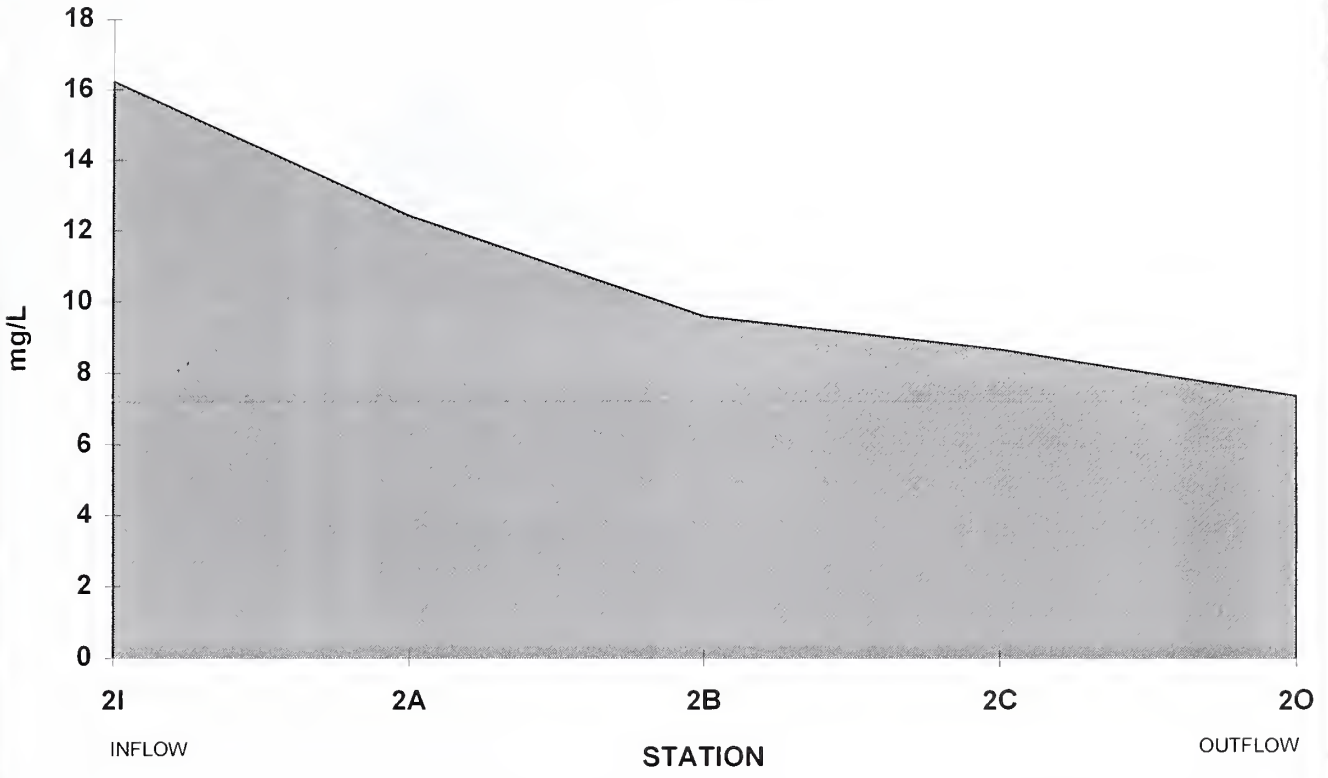

FIGURE 28. CELL 2 MEAN CONCENTRATIONS FOR AMMONIA NITROGEN

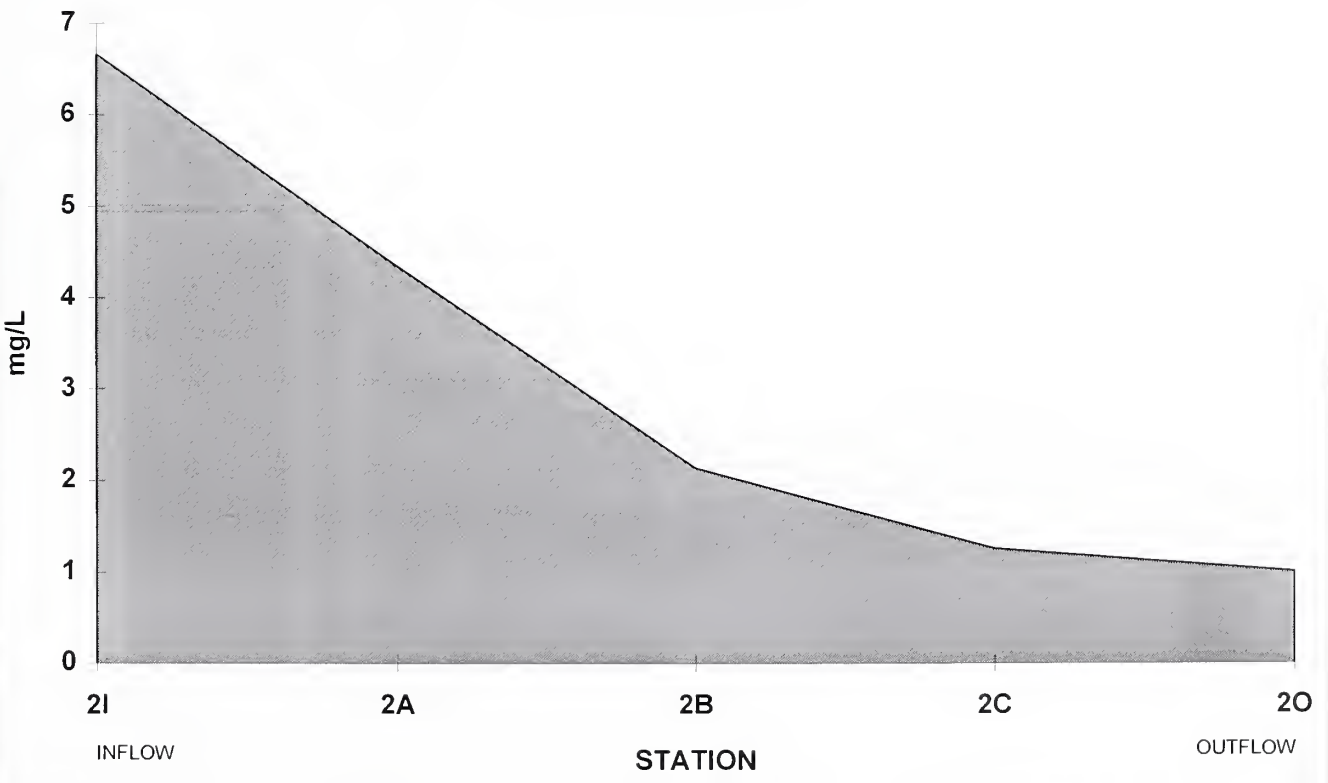

FIGURE 29. CELL 2 MEAN CONCENTRATIONS FOR NITRATE NITROGEN

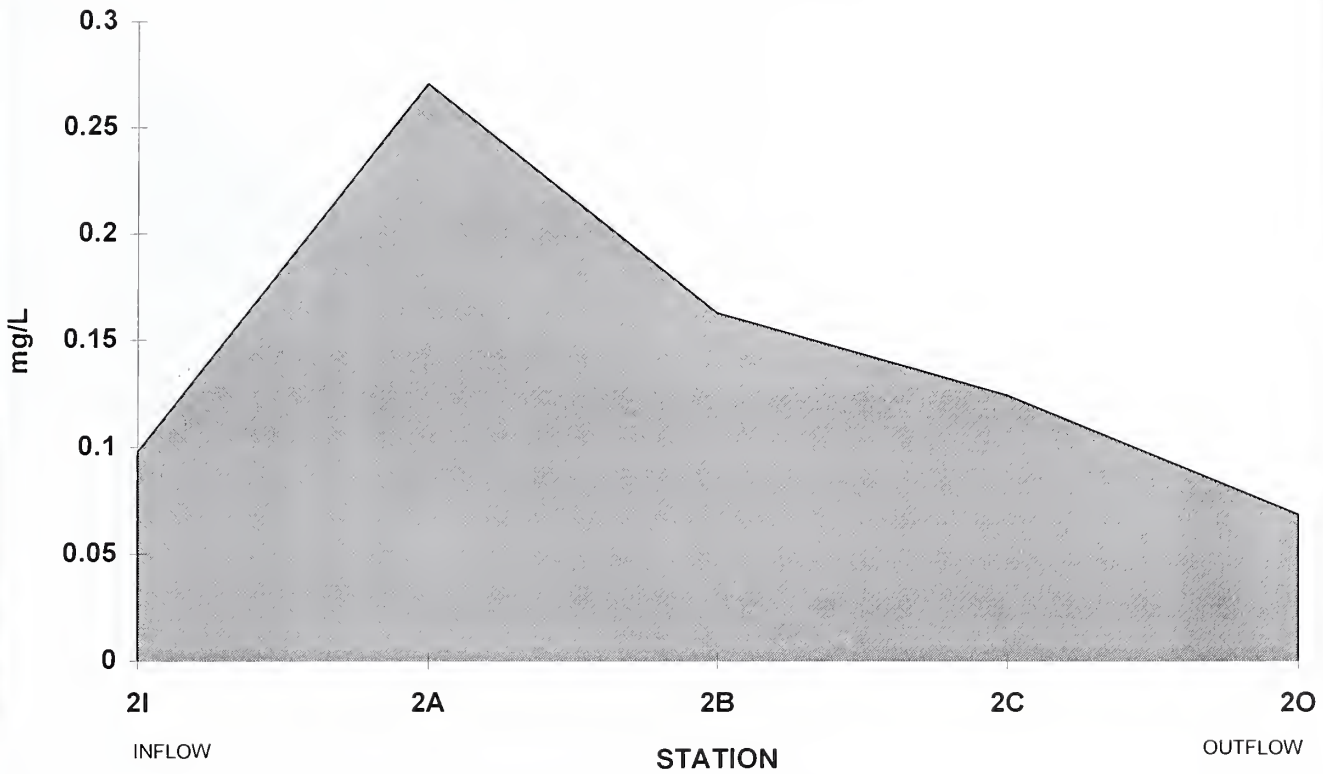

FIGURE 30. CELL 2 MEAN CONCENTRATIONS FOR TOTAL CHLOROPHYLL

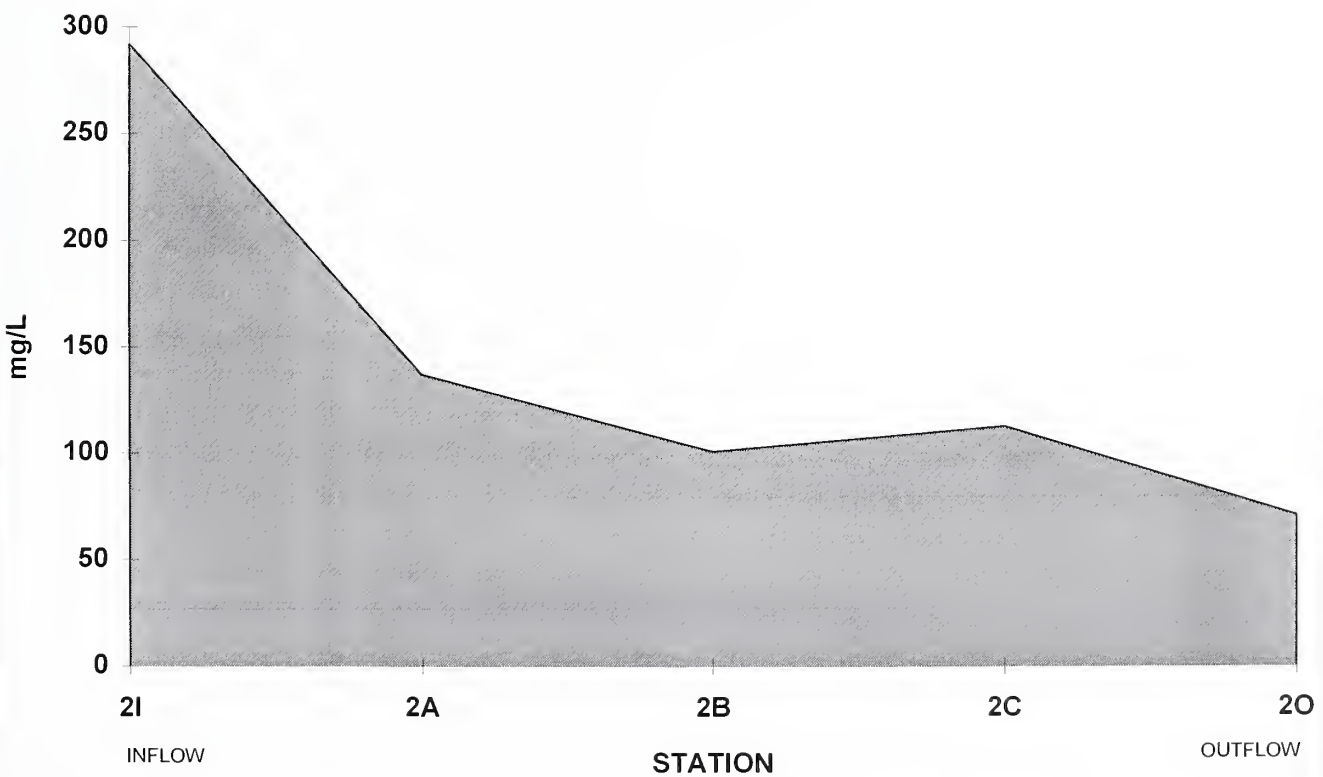

FIGURE 31. CELL 2 MEAN VALUES FOR 5-DAY CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND

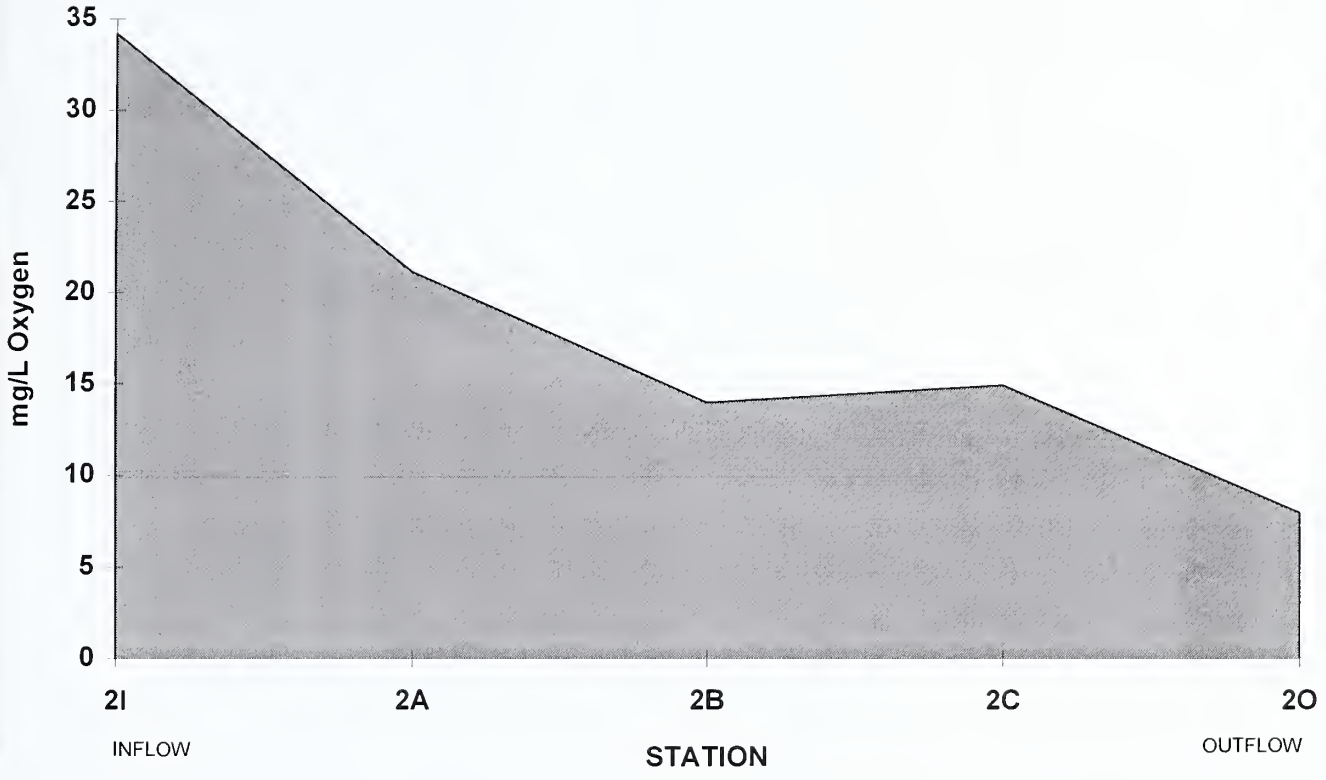

FIGURE 32. CELL 2 MEAN CONCENTRATIONS FOR TOTAL COLIFORMS